

Is the Higgs Mechanism of Fermion Mass Generation a Fact? From Theory to Experiment.

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Delaunay, Golling, GP & Soreq (13);
Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14);
GP, Soreq, Stamou & a (15)x2;
Ghosh, Gupta & GP (15)

Joint Experimental-Theoretical Physics Seminar



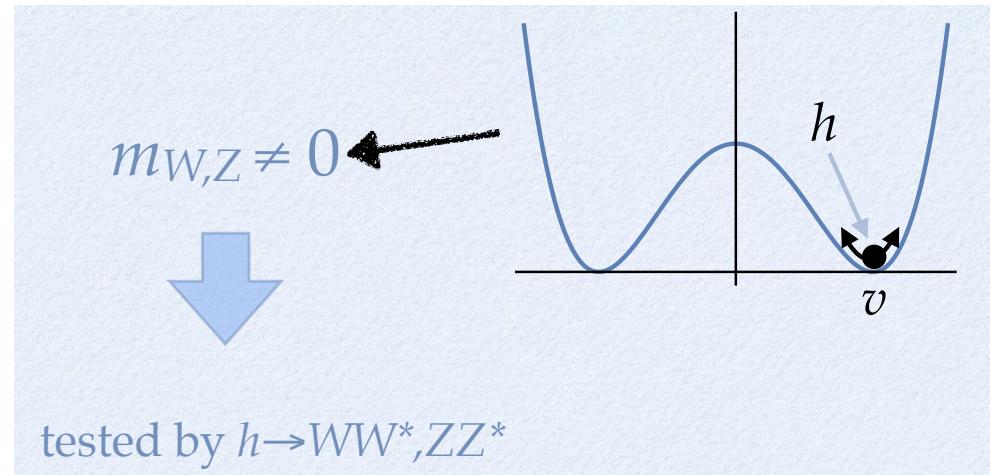
Outline

- ♦ Intro': Higgs & flavor physics within the Standard Model (SM) & beyond.
- ♦ Charming the Higgs, an inclusive approach. (charm-tagging)
Recent developments, establishing Higgs-quark non-univ. & more.
- ♦ Higgs to light-quark couplings, an exclusive approach.
- ♦ Outlook, future projections.

Minimality of the SM Higgs Mechanism

- ♦ Higgs in minimal SM, 2 roles:

- (i) induce electroweak (EW) gauge boson masses & unitarization (high-E consistency);

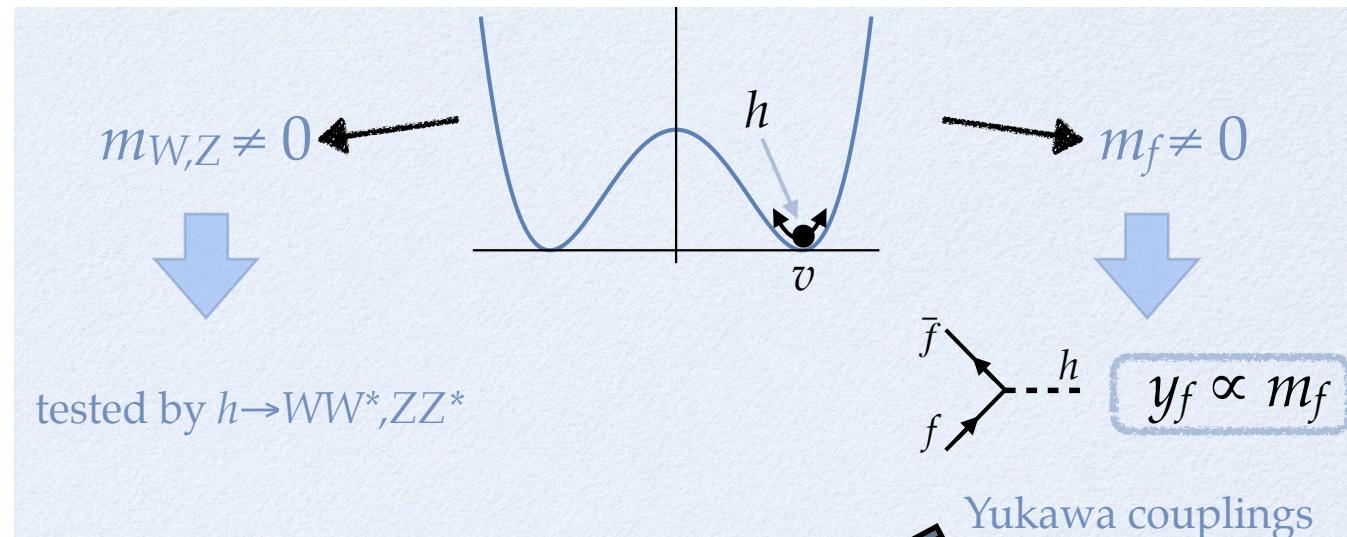


we know it's there, connected to the background value, no idea why it is light,
the hierarchy problem ...

Higgs & flavor physics within the SM

- ♦ Higgs in minimal SM, 2 roles:

- induce electroweak (EW) gauge boson masses & unitarization (high-E consistency);
- induce fermion masses & unitarization (high-E consistency).

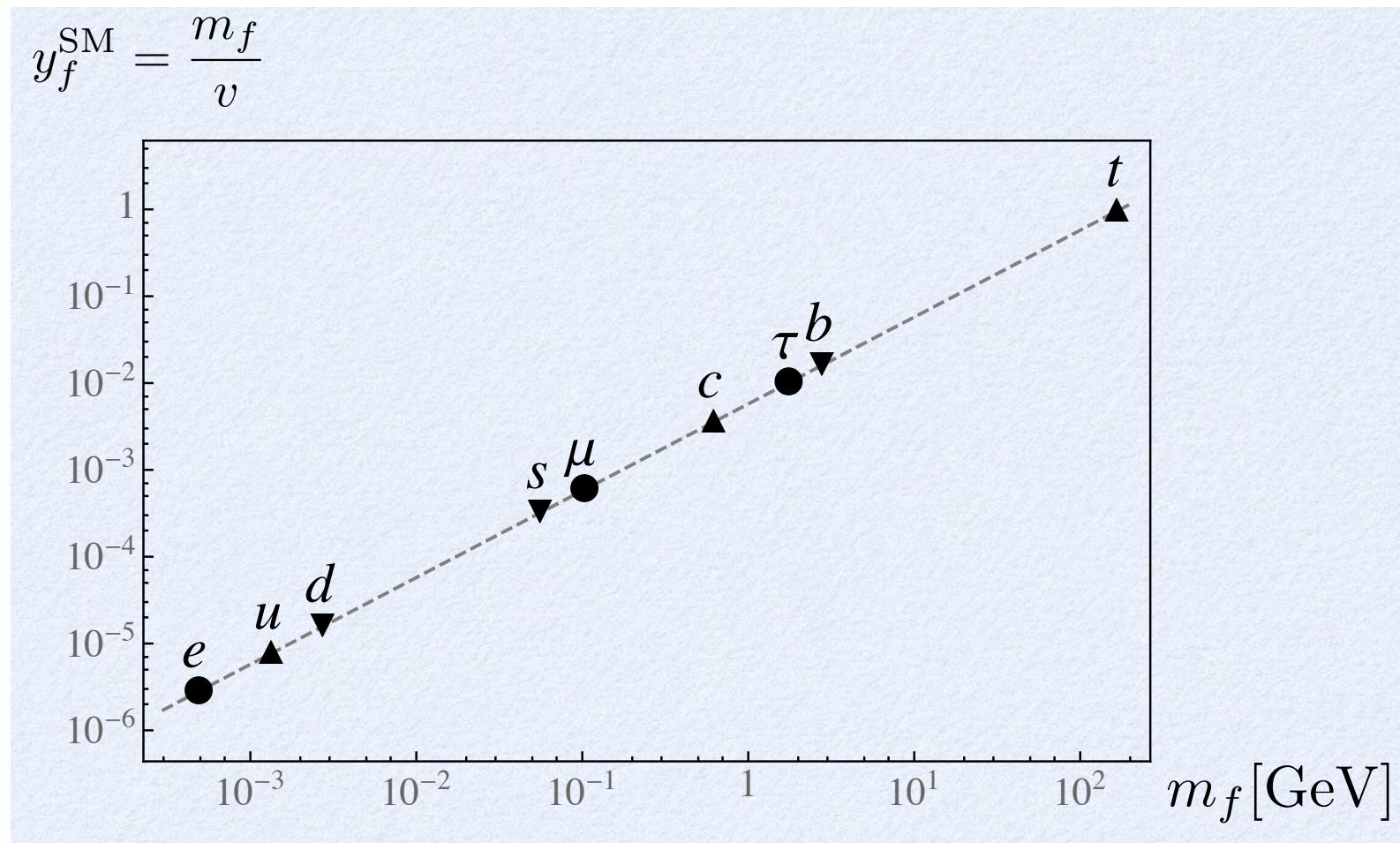


Tested only weakly;
only for the 3rd generation:

μ	ATLAS+CMS
τ	0.97 ± 0.23
b	0.71 ± 0.31
t	2.2 ± 0.6 (Moriond)

The other hierarchy (flavor) puzzle

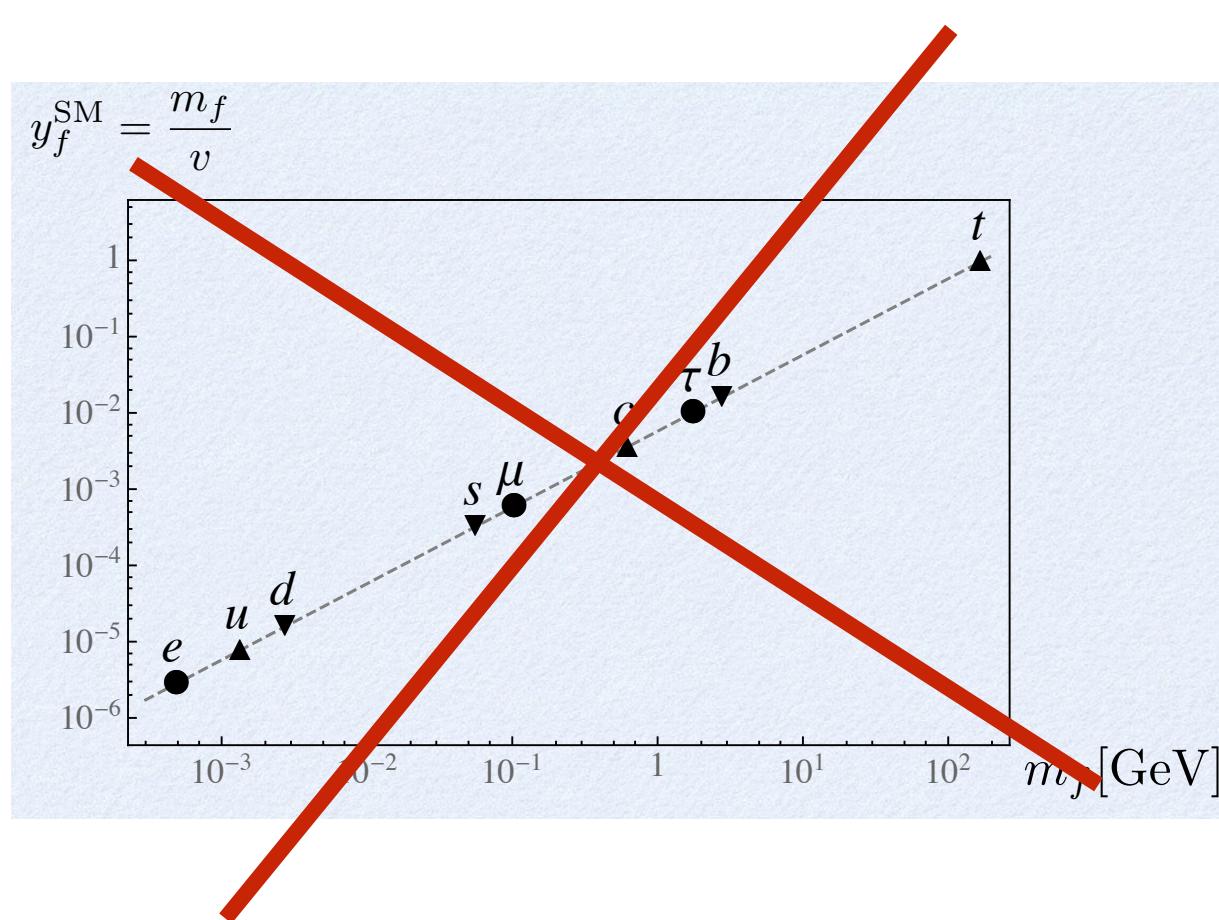
- ◆ The SM flavor parameters are small & hierarchical:



Y. Soreq, Student Colloquium, 2015

The other hierarchy (flavor) puzzle

- ♦ Maybe we've looked at it the wrong way?



Two extreme views

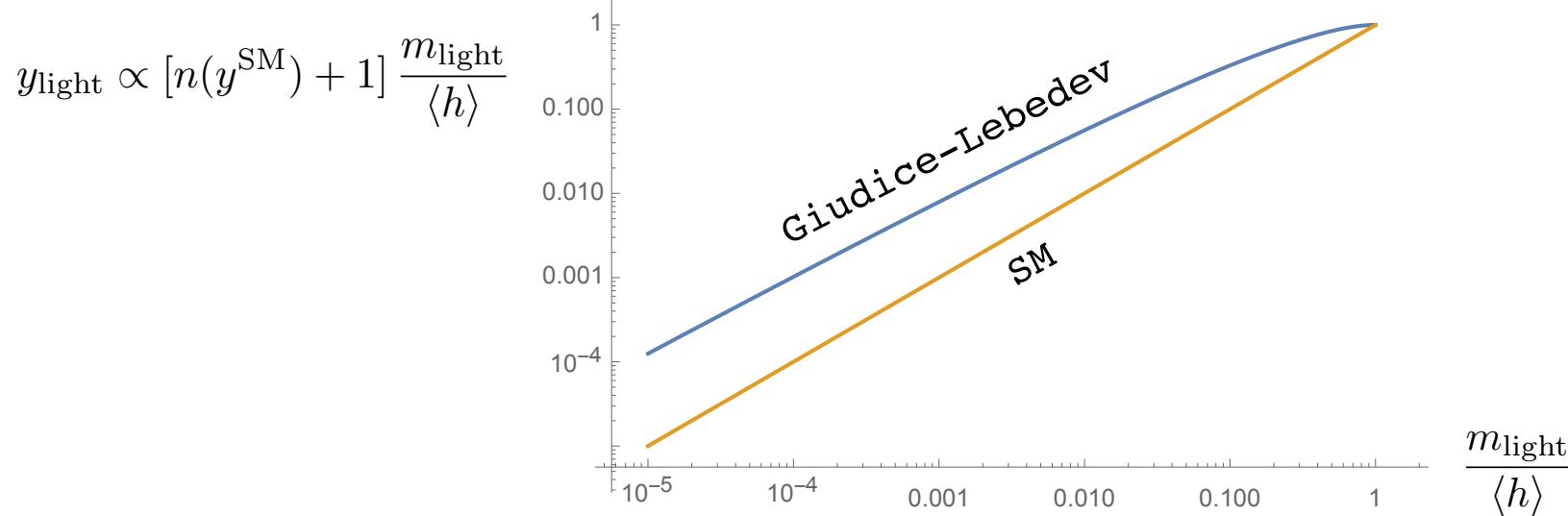
(i) Enhancement: Higgs Mechanism is also behind flavor generation.

Giudice & Lebedev (08); see analysis by Bauer, Carena, Gemmeler (15)

$$\frac{m_{\text{light}}}{\langle h \rangle} \propto \frac{\langle h \rangle^n}{\Lambda^n}, \quad y_{\text{light}} \propto (n+1) \frac{m_{\text{light}}}{\langle h \rangle}, \quad (\text{SM: } n=0)$$

To solve flavor puzzle: $n \sim 1 + \log(y^{\text{SM}})$

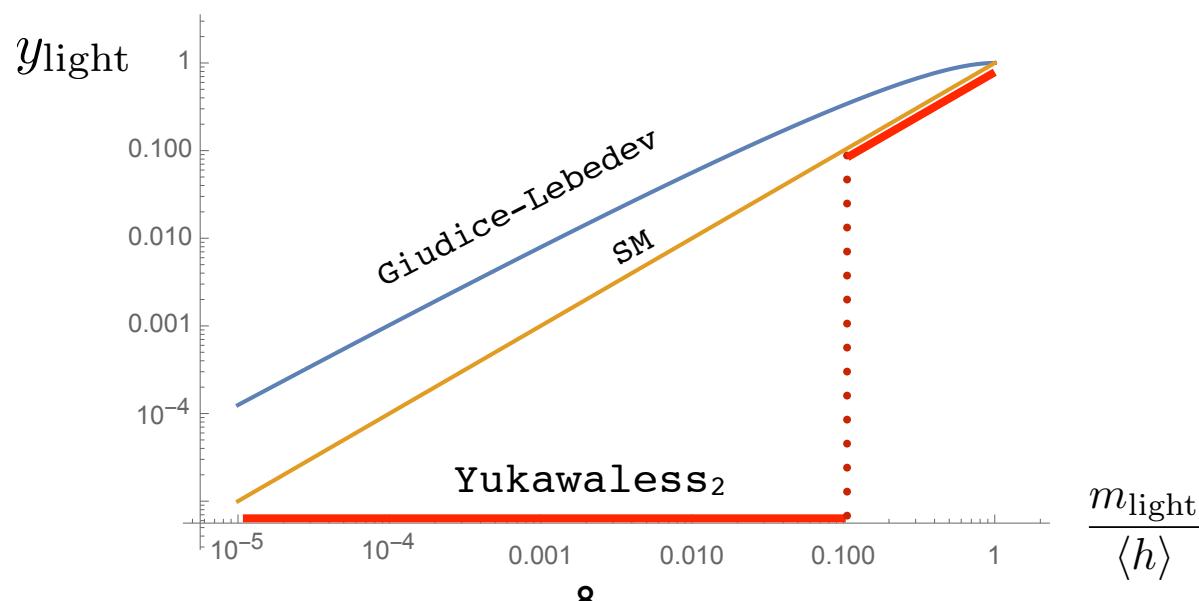
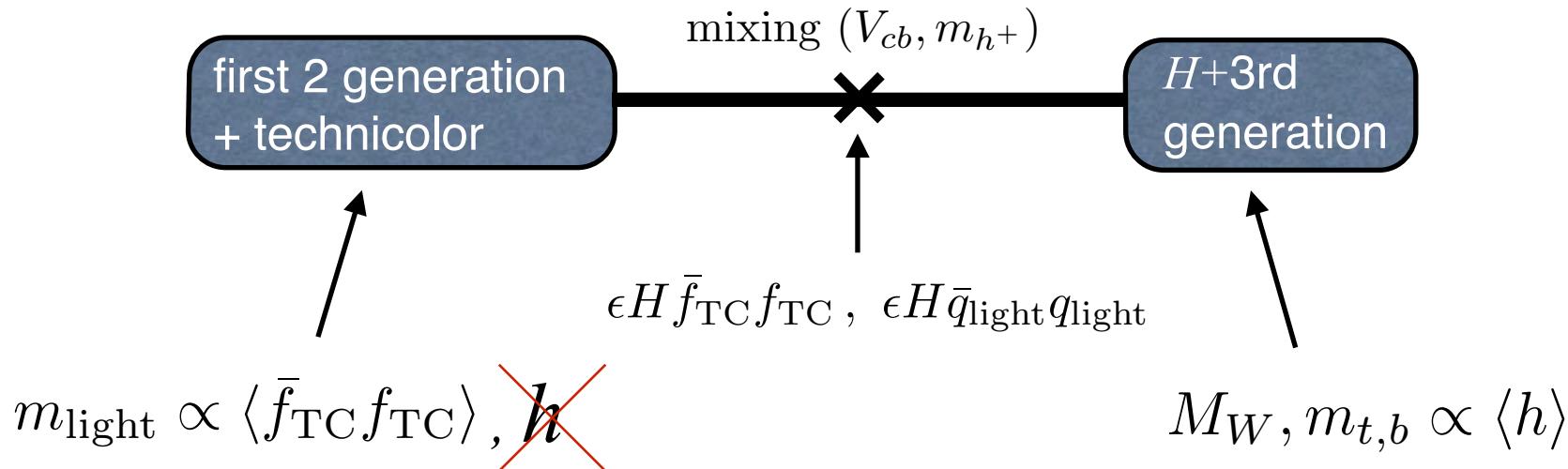
More generally: $\frac{y\langle h \rangle}{m} \sim \frac{dm}{dh} \times \frac{h}{m} \sim \frac{d \log m}{d \log h} \sim n_{\text{spectral}}$



Second limit: Yukawaless light fermions

(ii) Flavor & EW are linked, H is unrelated to (light) flavor => see flavor origin by eye:

Ghosh, Gupta & GP; see also: Altmannshofer, et al. (15)



Higgs & flavor physics within the SM

- ♦ Higgs in minimal SM, 2 roles:
 - (i) induce electroweak (EW) gauge boson masses & unitarization (high-E consistency);
 - (ii) induce fermion masses & unitarization (high-E consistency).
- (i) was already tested in a quantitative way (ii) much less & mostly for 3rd gen'. We focus on (ii), significant progress can be made.

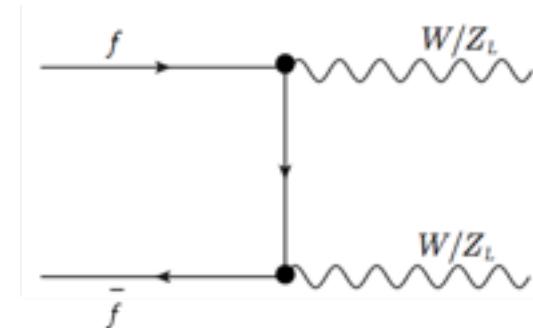
♦ What happens if we just write bare masses to fermions?

Unitarity violation:

$$q\bar{q} \rightarrow V_L V_L$$

(where V_L is the longitudinal boson)

$$\sqrt{s} \lesssim \frac{8\pi v^2}{\sqrt{6}m_{b,c,s,d,u}}$$
$$\approx 200, 1\times 10^3, 1\times 10^4, 2\times 10^5, 5\times 10^5 \text{ TeV}.$$



Appelquist & Chanowitz (87).

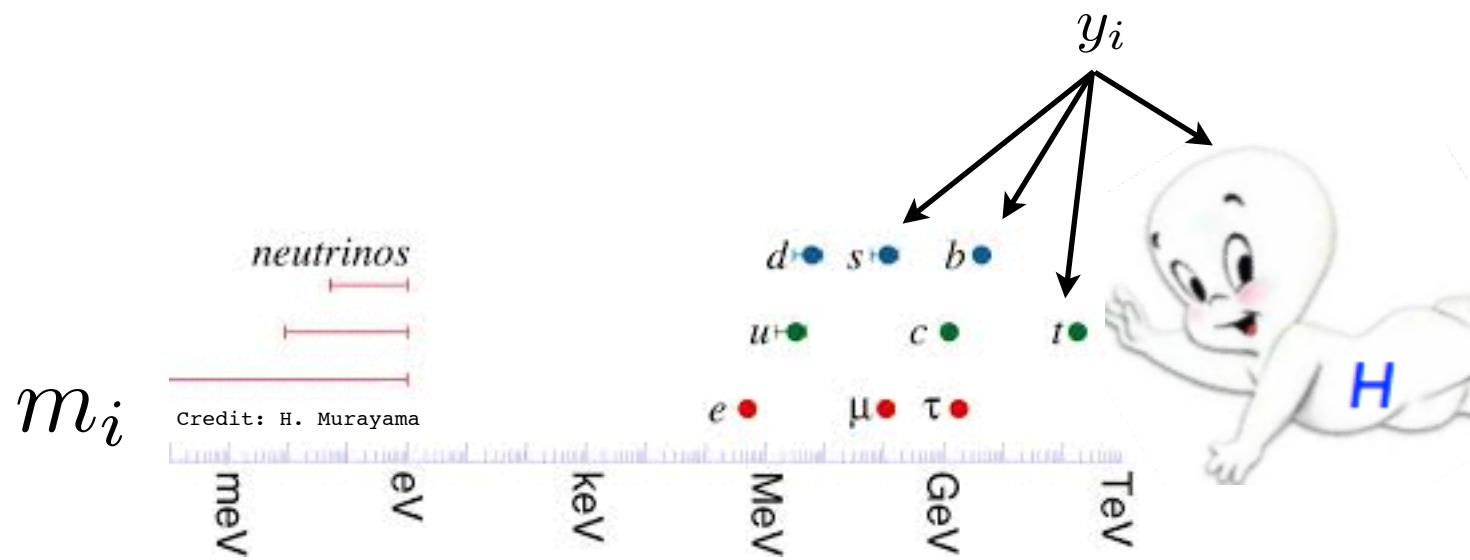
$$q\bar{q} \rightarrow nV_L \quad \sqrt{s} \lesssim 23, 31, 52, 77, 84 \text{ TeV}.$$

Maltoni, Niczyporuk & Willenbrock (01); Dicus and H.-J. He (05).

Higgs & flavor physics within the SM

- ♦ Recall: in the SM we have 2 type of interactions:
 - (i) gauge interactions: these are flavor blind/universal/same for all quarks;
 - (ii) Yukawa interactions: generation-dependent, non-universal, but to a single scalar.
- ♦ The above 2 facts + renormalizability leads to a simple relations, up two small corrections (1loop+GIM suppressed)

SM: Higgs couples like the mass - $y_i = m_i/v$

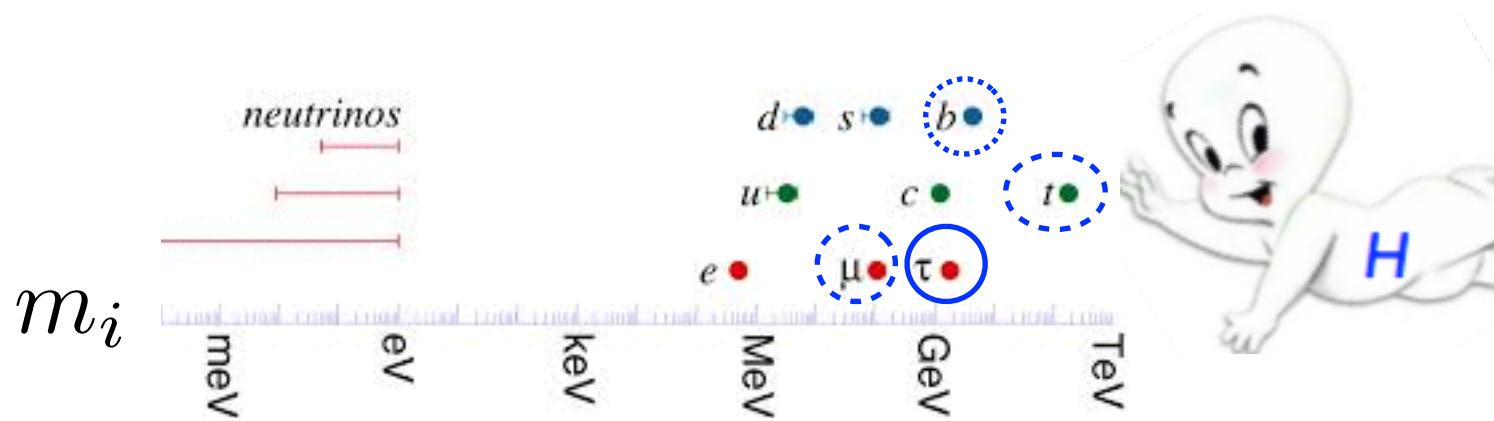


How much is known experimentally

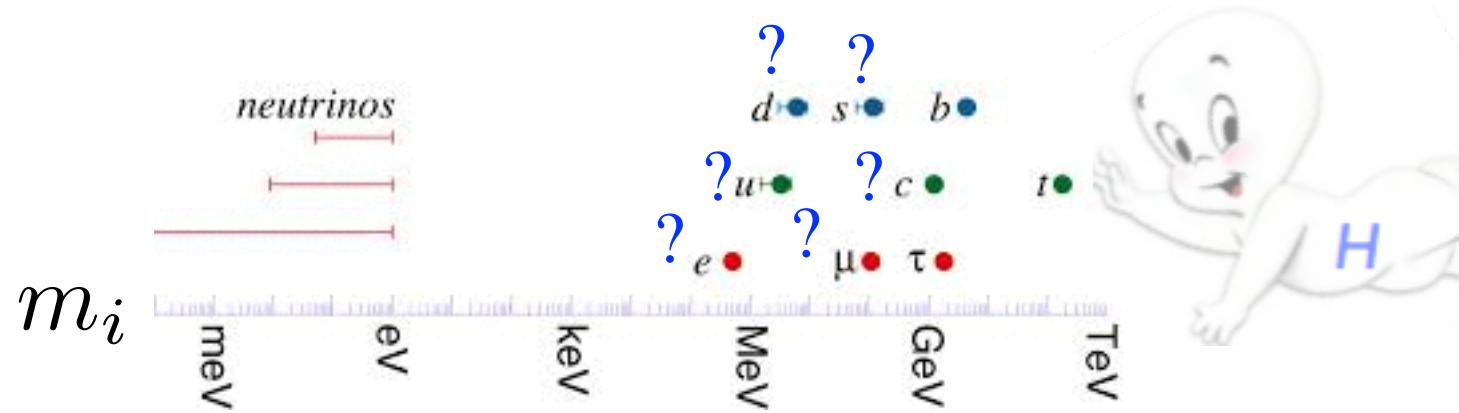
μ_x	ATLAS+CMS
T	0.97 ± 0.23
b	0.71 ± 0.31
t	2.2 ± 0.6 (Moriond)

$$\mu_\mu : \sigma \cdot \text{Br} < 7.0 \text{ (7.2)} (\sigma \cdot \text{Br})_{\text{SM}}$$

Universal couplings
~260 times SM

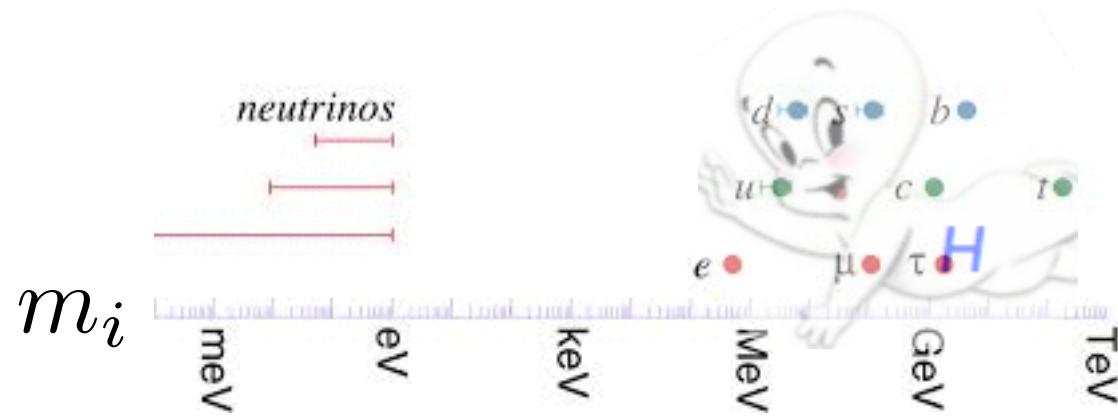


Higgs & flavor physics within the SM



Does the Higgs couples like the mass - $y_i = m_i/v$??

Higgs & flavor physics within the SM



Does the Higgs couples like the mass - $y_i = m_i/v$??

- ♦ The heart of the flavor puzzle rely on the above => could this be a wrong assumption?
- ♦ As Higgs is light and its decay (& production) is controlled by small couplings => small changes => dramatic change to phenomenology.

Charming the Higgs

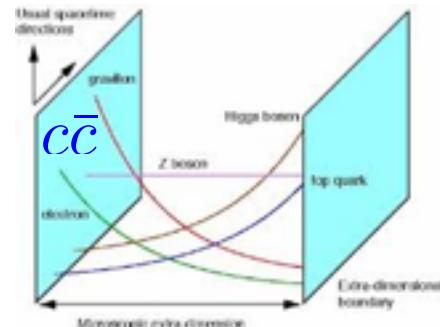
- ♦ Currently not much known directly on the charm Yukawa:
- (i) SM - $y_c = m_c/v \sim 0.3\% \Rightarrow BR(H \rightarrow c\bar{c}) \sim 3\%$
- ♦ However, as $y_b \sim 2\%$ & $BR(H \rightarrow b\bar{b}) \sim 60\%$, Higgs collider pheno' is susceptible to small perturbation.
- ♦ Enlarging charm Yukawa by few leads to dramatic changes, for instance:

$$\mathcal{L}_{\text{EFT}} \supset \lambda_{ij}^u \bar{Q}_i \tilde{H} U_j + \frac{g_{ij}^u}{\Lambda^2} \bar{Q}_i \tilde{H} U_j (H^\dagger H) + \text{h.c.}$$

$$\begin{aligned} \mathcal{L}_0 = \frac{h}{v} & \left[c_V (2m_W^2 W_\mu^+ W^{\mu-} + m_Z^2 Z_\mu Z^\mu) \right. \\ & \left. - \sum_q c_q m_q \bar{q} q - \sum_\ell c_\ell m_\ell \bar{\ell} \ell \right], \end{aligned}$$

$$\begin{aligned} \text{Diagram 1: } & \frac{v}{\sqrt{2}} \left(\lambda_{ij}^u + g_{ij}^u \frac{v^2}{2\Lambda^2} \right), \\ \text{Diagram 2: } & \frac{1}{\sqrt{2}} \left(\lambda_{ij}^u + 3g_{ij}^u \frac{v^2}{2\Lambda^2} \right). \end{aligned}$$

$$\Lambda \simeq \frac{63 \text{ TeV}}{\sqrt{|c_c - 1|}}$$

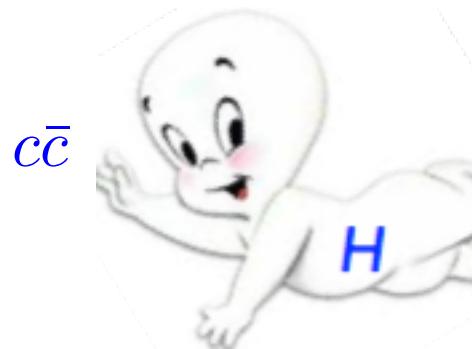


- ♦ Or is it simply technicolor for the light quarks ?

If you really care, more models: Delaunay, Grojean & GP (13); Kagan, GP, Volansky & Zupan (09); Dery, Efrati, Hiller, Hochberg & Nir (13); Giudice & Lebedev (08); Bishara, Brod, Uttayarat & Zupan (15)

Uncharming the Higgs, establishing non-universality & more

GP, Soreq, Stamou & Tobioka x2 (15)



Before talking about our work, 2 slides about an experimental progress

Charm tagging at the LHC

- ♦ In new ATLAS search for stop decay to charm + neutralino ($\tilde{t} \rightarrow c + \chi^0$) charm jet tagging has been employed for the first time at LHC
- ATLAS-CONF-2013-068
- ♦ charm jets identified by combining “information from the impact parameters of displaced tracks and topological properties of secondary and tertiary decay vertices” using multivariate techniques
 - ‘medium’ operating point: c-tagging efficiency = 20%, rejection factor of 5 for b jets, 140 for light jets. #’s obtained for simulated $t\bar{t}$ events for jets with $30 < p_T < 200$, and calibrated with data

More recently, constraining (non-deg.) scharms

- ◆ An interesting viable possibility is anarchic squark spectrum. Nir & Seiberg (93)

- ◆ Scenario still viable and the bounds on scharms are very weak.

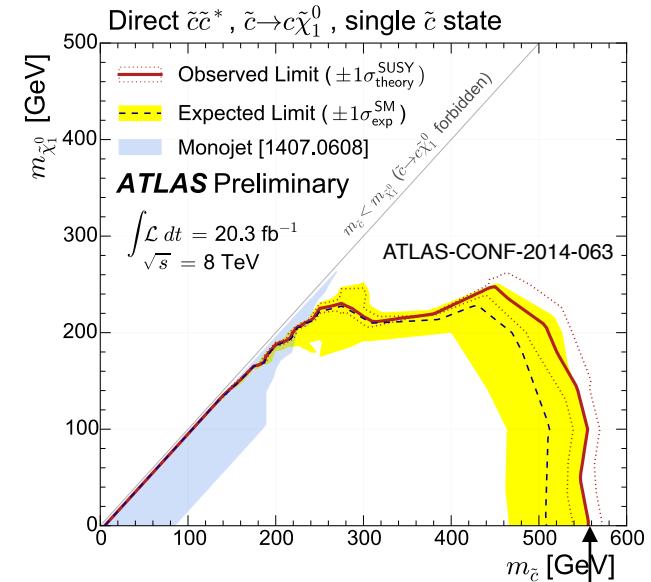
Gedalia, Kamenik, Ligeti & GP (12)
Mahbubani, Papucci, GP, Ruderman & Weiler (13)

- ◆ Has potential consequences for naturalness (“flavorful naturalness”).

Blanke, Giudice, Paradisi, GP & Zupan (13)

- ◆ ATLAS: light scharms search \w new working point for charm tagging:

$$\epsilon_c = 19\% \quad \epsilon_b = 12\%$$



Executive sum.: Constraining Higgs-charm univ.

GP, Soreq, Stamou & Tobioka (Feb/15)

- ♦ Existing data already constrain Higgs-quarks Univ..

- (i) Direct constraint: recast $VH(bb)$, taking advantage of 2 working point $c_c < 230$;
- (ii) the recent ATLAS search to $h \rightarrow J/\psi\gamma$ (see later) yield $c_c < 220$;
(assumes Higgs coupling to two photons and/or four leptons is not significantly modified by new physics);
- (iii) the direct measurement of the total width yield $c_c < 140$ (ATLAS), 120 (CMS) ;
- (iv) Global fit to the Higgs signal strength, $c_c < 6$;
- (v) tth data $\Rightarrow c_t > 1.0$ (equivalence to $c_c > 310$).

#1 Direct constraint: recast $VH(bb)$

GP, Soreq, Stamou & Tobioka (Feb/15)

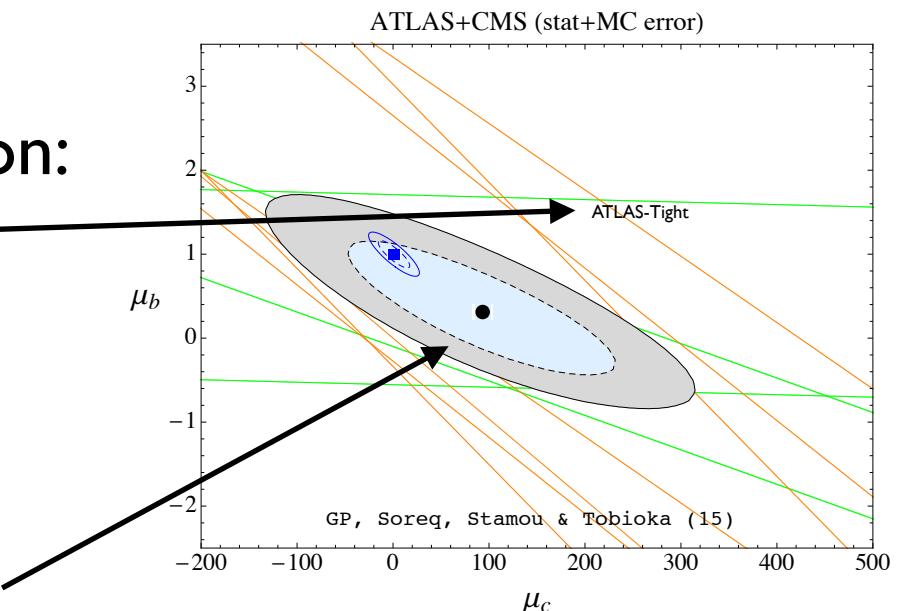
- ♦ Idea: use several charm-tagging working points of ATLAS & CMS in their $VH(bb)$ analysis.

$$\mu_b = \frac{\sigma}{\sigma_{SM}} \frac{\text{BR}_{b\bar{b}}}{\text{BR}_{b\bar{b}}^{SM}} \rightarrow \mu_b + \frac{\text{Br}_c^{SM}}{\text{Br}_b^{SM}} \frac{\epsilon_{c1} \epsilon_{c2}}{\epsilon_{b1} \epsilon_{b2}} \mu_c$$

where $\epsilon_{b_{1,2}}$ and $\epsilon_{c_{1,2}}$ are efficiencies to tag jets originating from bottom and charm quark, respectively. μ_c is normalized to be 1 in a case of the SM.

- ♦ Each working point yields flat direction:

ATLAS	Med	Tight	CMS	Loose	Med1	Med2	Med3	
	ϵ_b	70%		50%	ϵ_b	88%	82%	78%
	ϵ_c	20%	3.8%	ϵ_c	47%	34%	27%	21%

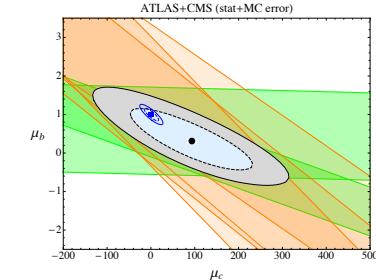


- ♦ However, combining points => bound.

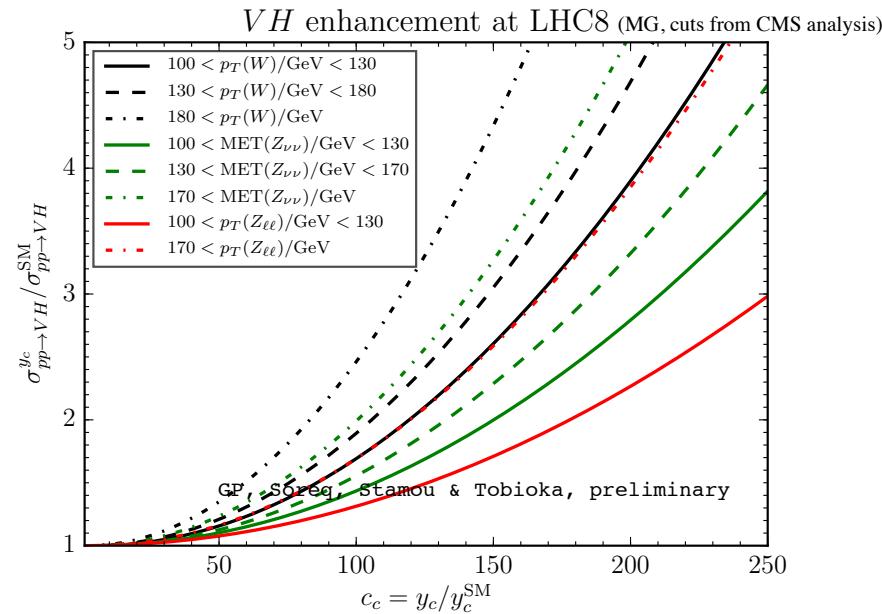
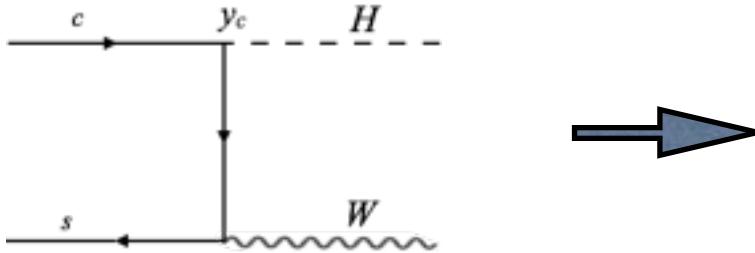
New production mechanism $VH(bb)$

GP, Soreq, Stamou & Tobioka (Feb/15)

- ♦ $\mu_c = \frac{\sigma}{\sigma^{\text{SM}}} \frac{\text{Br}}{\text{Br}_c^{\text{SM}}} \Rightarrow \text{w SM } VH\text{-production } \mu_c < 30 \Rightarrow \text{no constraint on } y_c.$



- ♦ However $\mu_c < 30$ for large $c_c > 50$ new production mechanism:



No runaway for c_c →

$$c_c < 250.$$

Constraining Higgs-quark universality #1 (model indep')

- ♦ New production eliminates the y_c runaway  $c_c < 230$ what about y_t ?

- ♦ ATLAS+CMS $t\bar{t}h$: $\mu_{t\bar{t}h}^{\text{avg}} = 2.2 \pm 0.6$,
fresh from Moriond

$$c_t > 1.0 \sqrt{\frac{\text{BR}_{\text{finals}}^{\text{SM}}}{\text{BR}_{\text{finals}}}} > 1.0$$

$$\frac{c_c}{c_t} = \frac{y_t^{\text{SM}}}{y_c^{\text{SM}}} \frac{y_c}{y_t} = 280 \frac{y_c}{y_t} < 230 \quad \Rightarrow \quad y_c < y_t !$$

GP, Soreq, Stamou & Tobioka (Feb/15)

Mano's talk: the method works much better via real c-tagging working point.

Constraining Higgs-quark universality #2+3

- ♦ Width bound: $\Gamma_h < 2.6 \text{ GeV (ATLAS)}, \quad \Gamma_h < 1.7 \text{ GeV (CMS)} \Rightarrow \boxed{c_c < 140, 120}.$

GP, Soreq, Stamou & Tobioka (Feb/15)

- ♦ Interpretation of ATLAS recent $h \rightarrow J/\psi\gamma$ (1501.03276): $\sigma(pp \rightarrow h) \times \text{BR}_{h \rightarrow J\psi\gamma} < 33 \text{ fb},$

- ♦ This implies (see later): $\Gamma_{h \rightarrow J/\psi\gamma} = 1.42 (\kappa_\gamma - 0.087 \kappa_c)^2 \times 10^{-8} \text{ GeV}$

Bodwin, Petriello, Stoynev & Velasco (13); Bodwin, Chung, Ee, Lee & Petriello (14)

- ♦ Getting rid of production: $\mathcal{R}_{J/\psi, Z} = \frac{\sigma(pp \rightarrow h) \times \text{BR}_{h \rightarrow J/\psi\gamma}}{\sigma(pp \rightarrow h) \times \text{BR}_{h \rightarrow ZZ^* \rightarrow 4\ell}} = \frac{\Gamma_{h \rightarrow J/\psi\gamma}}{\Gamma_{h \rightarrow ZZ^* \rightarrow 4\ell}} = 2.79 \frac{(\kappa_\gamma - 0.087 \kappa_c)^2}{\kappa_V^2} \times 10^{-2},$

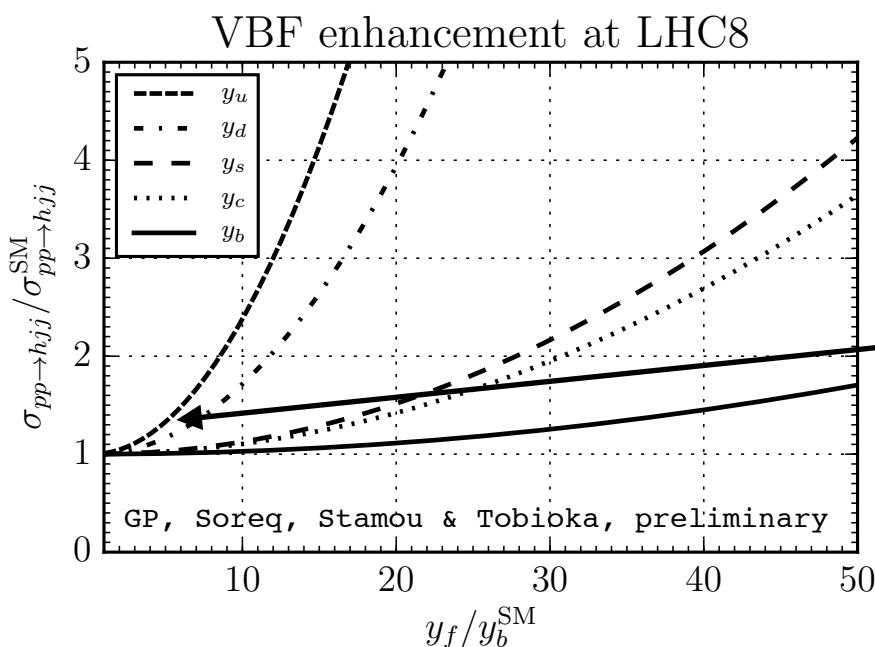
$$\mathcal{R}_{J/\psi, Z} = \frac{33 \text{ fb}}{\mu_{ZZ^*} \sigma^{\text{SM}} \text{BR}_{h \rightarrow ZZ^* \rightarrow 4\ell}^{\text{SM}}} < 9.32 \quad \longrightarrow \quad \boxed{c_c < 210 c_V + 11 c_\gamma}.$$

(LEP: $c_V = 1.08 \pm 0.07$)

Finally global analysis

- ♦ The conventional way of doing the fit leads to: $C_c < 6$.
- ♦ It is equivalence to the invisible (untagged) Higgs decay bound, driven by VBF:

$$\mu_{\text{VBF} \rightarrow h \rightarrow WW^*} = 1.27^{+0.44+0.30}_{-0.40-0.21} = 1.27^{+0.53}_{-0.45}, \quad \Leftrightarrow \quad \mu_{\text{VBF} \rightarrow h \rightarrow WW^*} = (\kappa_V^2 + \bar{\sigma}_{\text{VBF}}^{\text{non-SM}}) \frac{\kappa_V^2}{R_\Gamma}$$

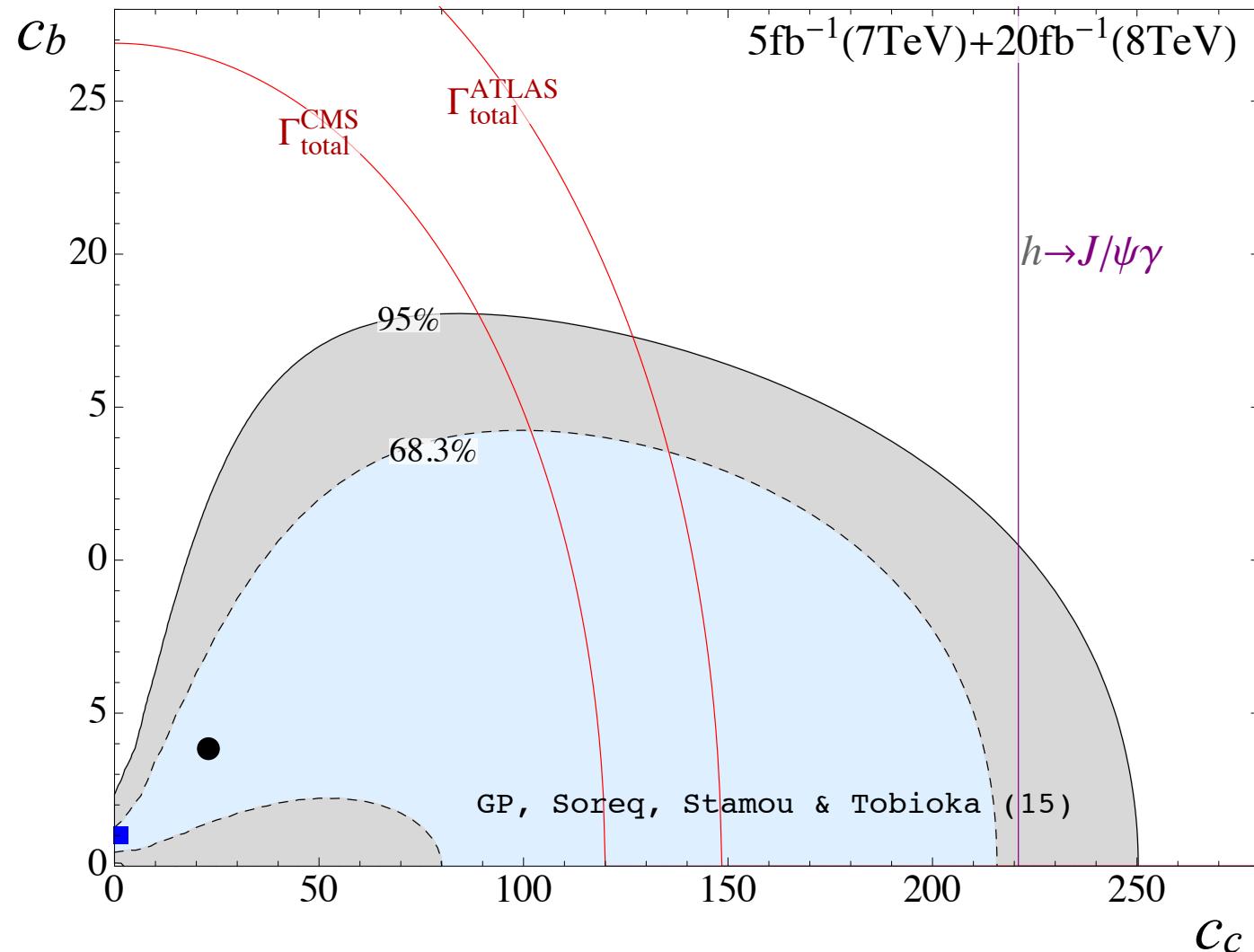


always set to zero, however not necessarily negligible.

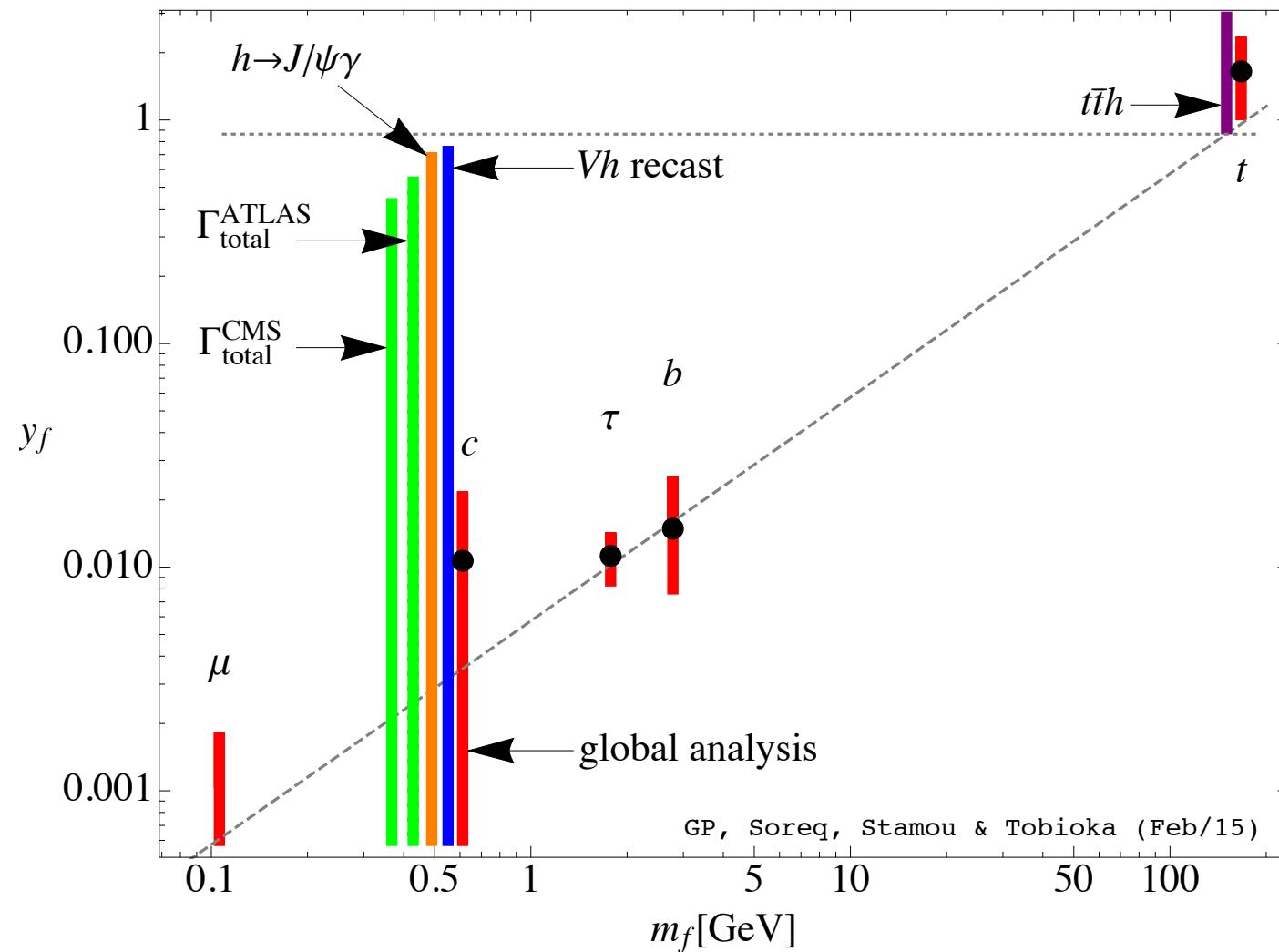
Currently small effect but might not be in the future.

VBF & Vh can be compared to other machines, leptons? hadrons?

Showing all constraints together



Summary plot ...



An Exclusive Window onto Higgs Yukawa Couplings to light quarks

Bodwin, Petriello, Stoynev & Velasco (13)
Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)



Exclusive path towards Higgs-light quark couplings

- ♦ Use the eff. Lagrangian:
$$\mathcal{L}_{\text{eff}} = - \sum_{q=u,d,s} \bar{\kappa}_q \frac{m_b}{v} h \bar{q}_L q_R - \sum_{q \neq q'} \bar{\kappa}_{qq'} \frac{m_b}{v} h \bar{q}_L q'_R + h.c.$$
$$+ \kappa_Z m_Z^2 \frac{h}{v} Z_\mu Z^\mu + 2\kappa_W m_W^2 \frac{h}{v} W_\mu W^\mu + \kappa_\gamma A_\gamma \frac{\alpha}{\pi} \frac{h}{v} F^{\mu\nu} F_{\mu\nu},$$

Notice that: $\bar{\kappa}_q = y_q / y_b^{\text{SM}}$, (sorry different notation)

in the SM:

$$\bar{\kappa}_s = m_s/m_b \simeq 0.020$$

$$\bar{\kappa}_d = m_d/m_b \simeq 1.0 \cdot 10^{-3}$$

$$\bar{\kappa}_u = m_u/m_b \simeq 4.7 \cdot 10^{-4}$$

$$\kappa_\gamma = \kappa_V = 1$$

Exclusive path towards Higgs-light quark couplings

Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

♦ Use the eff. Lagrangian:

$$\begin{aligned} \mathcal{L}_{\text{eff}} = & - \sum_{q=u,d,s} \bar{\kappa}_q \frac{m_b}{v} h \bar{q}_L q_R - \sum_{q \neq q'} \bar{\kappa}_{qq'} \frac{m_b}{v} h \bar{q}_L q'_R + h.c. \\ & + \kappa_Z m_Z^2 \frac{h}{v} Z_\mu Z^\mu + 2\kappa_W m_W^2 \frac{h}{v} W_\mu W^\mu + \kappa_\gamma A_\gamma \frac{\alpha}{\pi} \frac{h}{v} F^{\mu\nu} F_{\mu\nu}, \end{aligned}$$

Notice that: $\bar{\kappa}_q = y_q / y_b^{\text{SM}}$,

where generically:

$$|\bar{\kappa}_u| < 0.98, \quad |\bar{\kappa}_d| < 0.93, \quad |\bar{\kappa}_s| < 0.70$$

varying only one at the time (95%CL)

$$|\bar{\kappa}_u| < 1.3, \quad |\bar{\kappa}_d| < 1.4, \quad |\bar{\kappa}_s| < 1.4$$

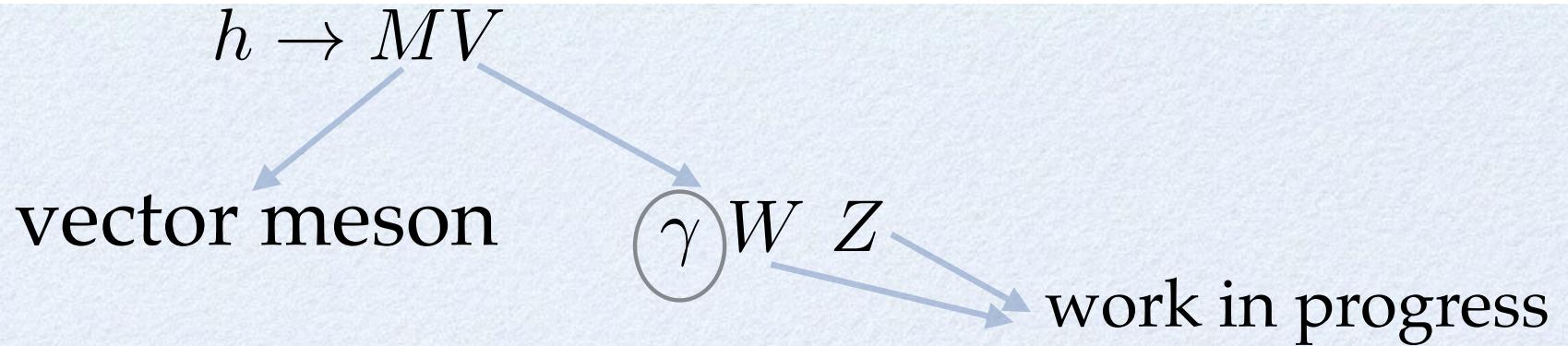
varying all couplings (95%CL)

$$|\bar{\kappa}_{qq'}| < 0.6 \text{ (1)} \quad \text{for } q, q' \in u, d, s, c, b \text{ and } q \neq q'$$

same for the flavor violating case

(FCNC non-robust bound: $|\bar{\kappa}_{bs}| < 8 \cdot 10^{-2}$) Harnik, Kopp & Zupan; Blankenburg, Ellis, Isidori, (12)

The main idea



Bodwin, Petriello,
Stoynev, Velasco
1306.5770

$$h \rightarrow J/\psi \gamma \longrightarrow y_c$$

$$\begin{aligned} \phi\gamma &\longrightarrow y_s \\ h \rightarrow \rho\gamma &\longrightarrow y_d, y_u \\ \omega\gamma &\longrightarrow y_d, y_u \end{aligned}$$

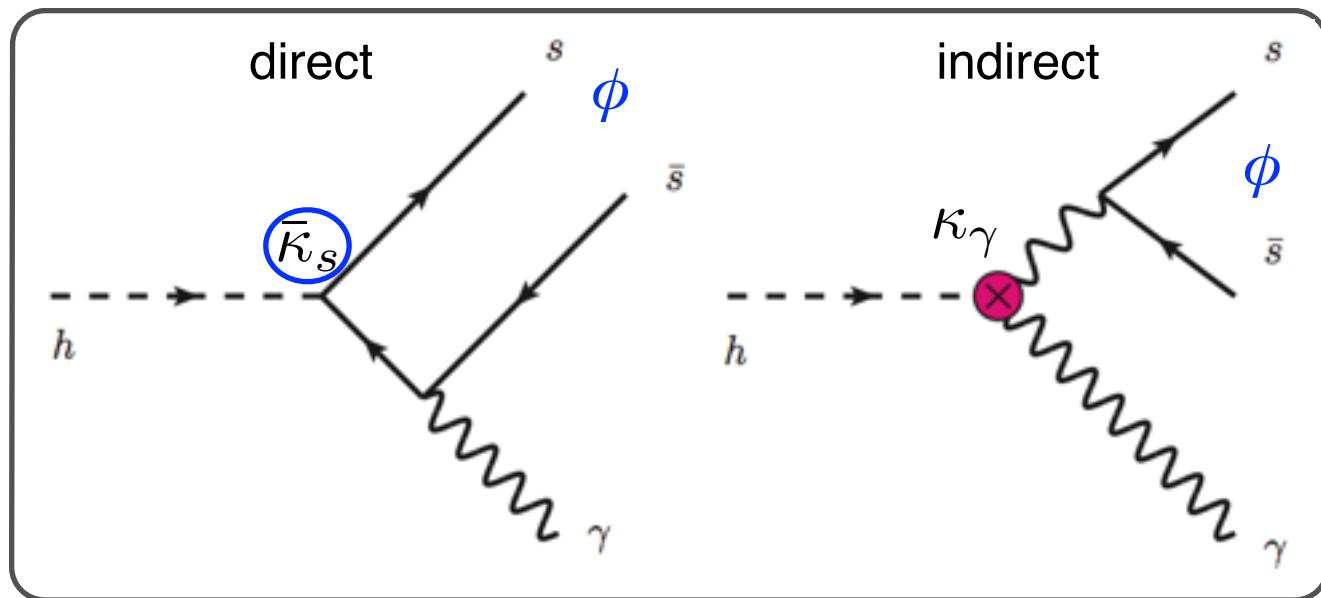
Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

Adding off-diagonal: $h \rightarrow \bar{B}^{0*}\gamma, h \rightarrow \bar{B}^{0*}\gamma, h \rightarrow K^{0*}\gamma, h \rightarrow D^{0*}\gamma$

Ex.: $h \rightarrow \phi\gamma$

$$\Gamma_{h \rightarrow \phi\gamma} = \frac{1}{8\pi} \frac{1}{m_h} |M_{ss}^\phi|^2,$$

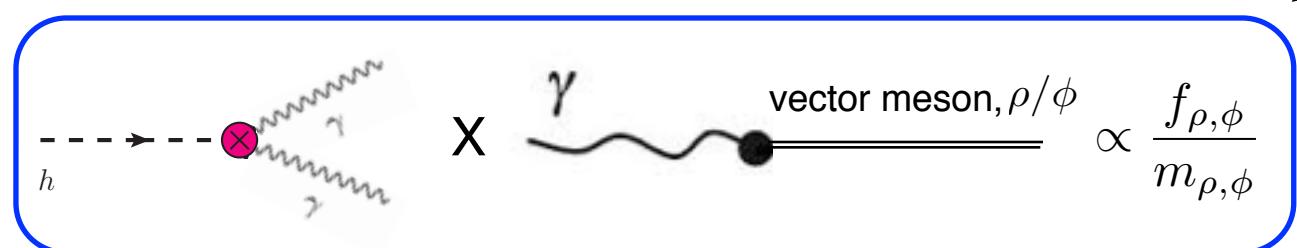
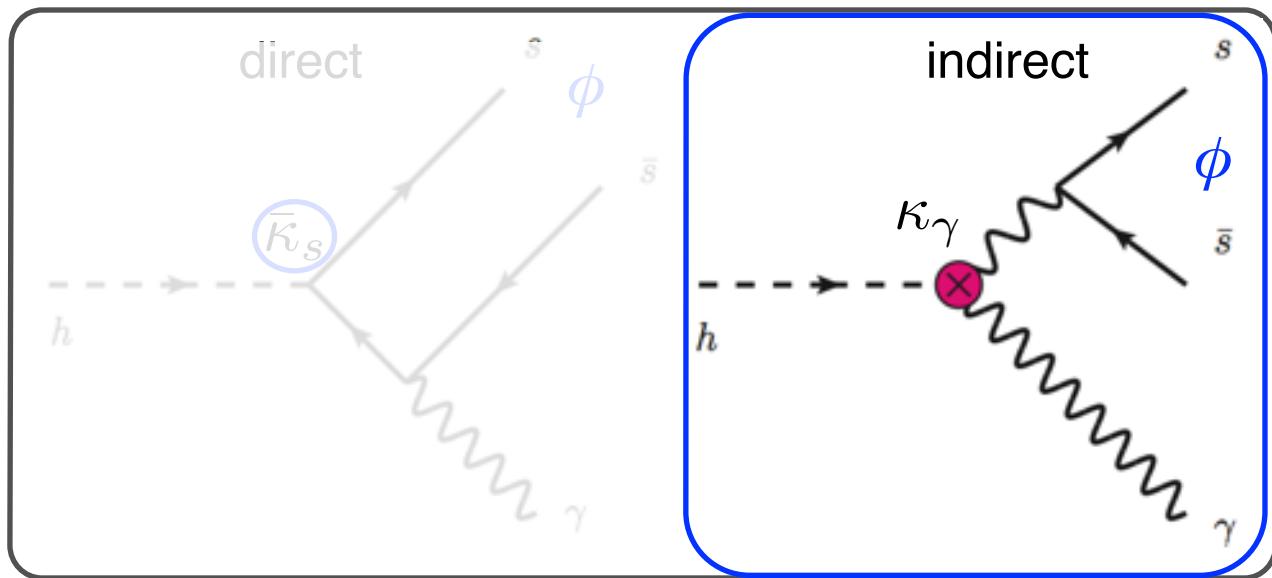
- Two paths to get $h \rightarrow \phi\gamma$:



- Let us understand them one by one.

Ex.: $h \rightarrow \phi\gamma$, indirect contribution

- Two paths to get $h \rightarrow \phi\gamma$:



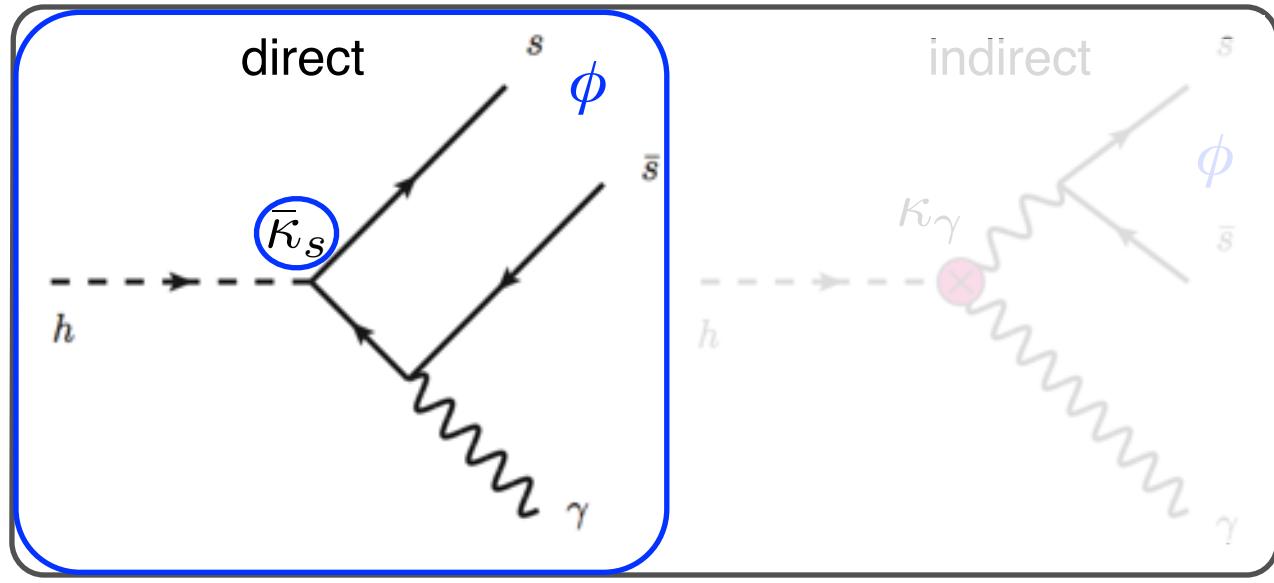
$(f_\phi = 0.235(5) \text{ GeV})$

from experiment, $\phi \rightarrow e^+e^-$

$$(M_{ss}^\phi)_{\text{indir}} \approx \frac{f_{\rho,\phi}}{m_{\rho,\phi}} \kappa_\gamma A_\gamma \frac{4\alpha m_h^2}{\pi v}$$

Ex.: $h \rightarrow \phi\gamma$, direct contribution

- Two paths to get $h \rightarrow \phi\gamma$:



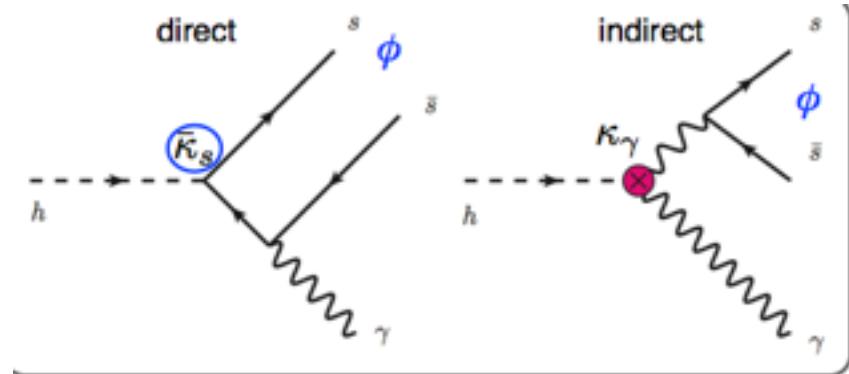
The diagram shows the same "direct" Feynman diagram as above. Below it is a formula: $\propto \frac{\bar{\kappa}_s m_b}{v} \frac{f_{\rho,\phi}^\perp}{m_h}$. Below the formula is the text: ("local" structure : $\bar{s}\sigma_{\mu\nu}s \times F^{\mu\nu}$)

from experiment, $\phi \rightarrow e^+e^-$
 $(f_\perp^\phi = 0.191(28))$

$(M_{ss}^\phi)_{\text{dir}} \approx \frac{\bar{\kappa}_s m_b}{v} f_\phi^\perp$

Final result for the $\text{BR}(h \rightarrow \phi\gamma)$

$$\Gamma_{h \rightarrow \phi\gamma} = \frac{1}{8\pi} \frac{1}{m_h} |M_{ss}^\phi|^2,$$



- ◆ The resulting sensitivity:

$$\frac{\text{BR}_{h \rightarrow \phi\gamma}}{\text{BR}_{h \rightarrow b\bar{b}}} = \frac{\kappa_\gamma [(3.0 \pm 0.3)\kappa_\gamma - 0.78\bar{\kappa}_s] \cdot 10^{-6}}{0.57\bar{\kappa}_b^2},$$

$$\frac{\text{BR}_{h \rightarrow \rho\gamma}}{\text{BR}_{h \rightarrow b\bar{b}}} = \frac{\kappa_\gamma [(1.9 \pm 0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d] \cdot 10^{-5}}{0.57\bar{\kappa}_b^2},$$

$$\frac{\text{BR}_{h \rightarrow \omega\gamma}}{\text{BR}_{h \rightarrow b\bar{b}}} = \frac{\kappa_\gamma [(1.6 \pm 0.17)\kappa_\gamma - 0.59\bar{\kappa}_u - 0.29\bar{\kappa}_d] \cdot 10^{-6}}{0.57\bar{\kappa}_b^2},$$

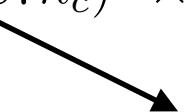
Similar holds
for 1st generation:

Comment added

Koenig & Neubert (15) obtained a weaker bound than what shown above.

The reason for this is three fold:

- (i) we normalised the signal strength of the exclusive channels by μ_{ZZ^*} to reduce the dependence on κ_γ by 10%.
- (ii) include the order 10% theoretical uncertainty in the bound.
- (iii) KN: modified central value of matrix element => 40% reduction the dependence of κ_c => 40% increase in the bound:

$$\Gamma_{h \rightarrow J/\psi \gamma} = 1.42 (\kappa_\gamma - 0.087 \kappa_c)^2 \times 10^{-8} \text{ GeV}$$

$$0.063$$

Higgs to light quarks sensitivity - projections for HL-LHC

GP, Soreq, Stamou & Tobioka (15).

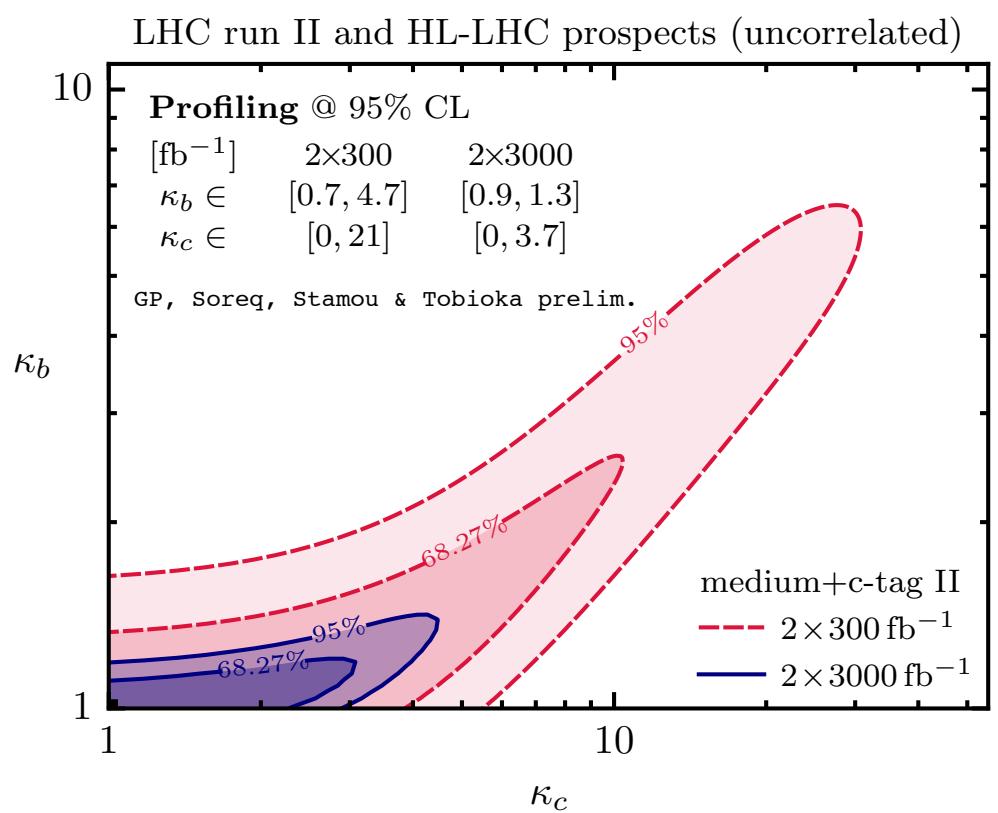
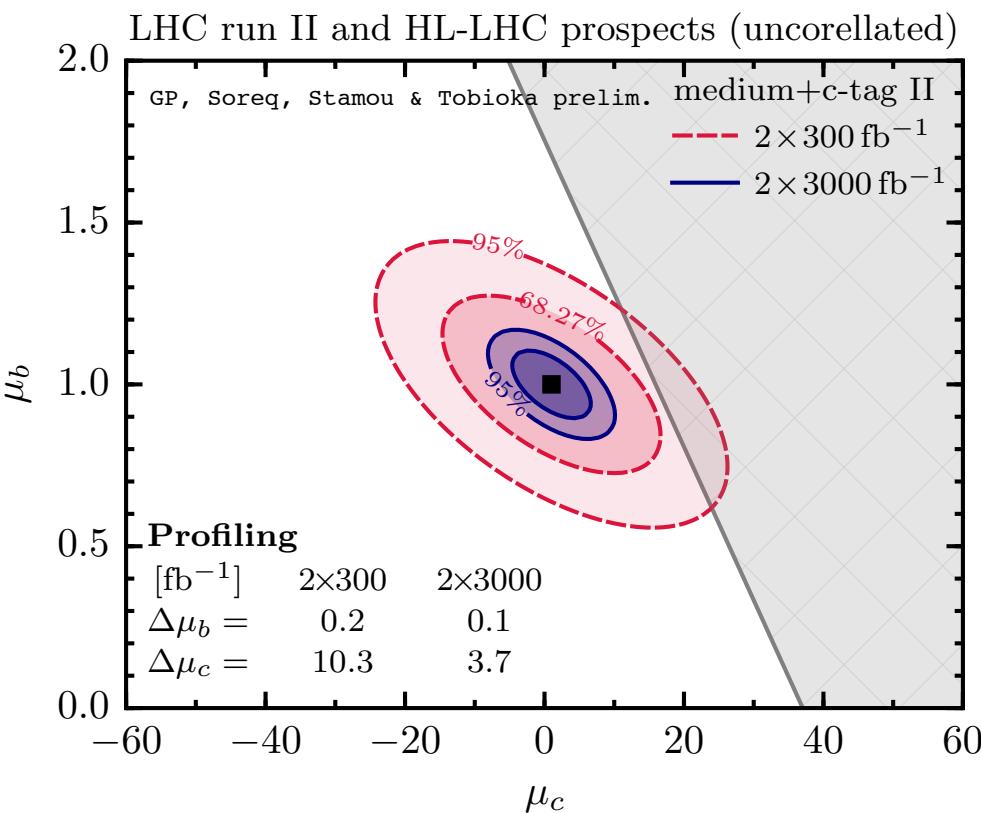
Inclusive, charm-tagging

	ϵ_b	ϵ_c	ϵ_l
<i>b</i> -tagging	70%	20%	1.25%
<i>c</i> -tagging I	13%	19%	0.5%
<i>c</i> -tagging II	20%	30%	0.5%

ATLAS, arXiv:1501.01325.

$$\kappa_c \equiv y_c/y_c^{\text{SM}},$$

$[\text{fb}^{-1}]$	2×300	2×3000
$\kappa_c \in$	$[0, 21]$	$[0, 3.7]$



Exclusive projections

- ◆ ATLAS result, mapped out the dominant BG: $\sigma_h \text{BR}_{J/\psi\gamma} < 33 \text{ fb}$ arXiv:1501.03276 [hep-ex]

- ◆ Useful to define ratio that is independent of the production:

GP, Soreq, Stamou & Tobioka (Feb/15)

$$\mathcal{R}_{M\gamma,Z} \equiv \frac{\sigma_h \text{BR}_{M\gamma}}{\sigma_h \text{BR}_{ZZ^*\rightarrow 4\ell}} \simeq \frac{\Gamma_{M\gamma}}{\Gamma_{ZZ^*\rightarrow 4\ell}} = \begin{cases} 2.8 \times 10^{-2} (\kappa_\gamma - 8.7 \times 10^{-2} \kappa_c)^2 / \kappa_V^2 & M = J/\psi \\ 2.4 \times 10^{-2} (\kappa_\gamma - 2.6 \times 10^{-3} \kappa_s)^2 / \kappa_V^2 & M = \phi \end{cases},$$

Bodwin, Petriello, Stoynev & Velasco (13); Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

$$\text{BR}_{J/\psi\gamma}^{\text{SM}} = 2.9 \times 10^{-6}, \text{BR}_{\phi\gamma}^{\hat{\text{SM}}} = 3.0 \times 10^{-6}, \text{BR}_{ZZ^*\rightarrow 4\ell}^{\text{SM}} = 1.25 \times 10^{-4}.$$

- ◆ For a given upper bound, $\bar{\mu}_M$, on an exclusive mode, we can write:

$$\mathcal{R}_{M\gamma,Z} < \frac{\bar{\mu}_M}{\mu_{ZZ^*}} \frac{\text{BR}_{M\gamma}^{\text{SM}}}{\text{BR}_{ZZ^*\rightarrow 4\ell}^{\text{SM}}}, \quad \bar{\mu}_M \equiv \frac{\bar{\sigma}_h \overline{\text{BR}}_{M,\gamma}}{\sigma_h^{\text{SM}} \text{BR}_{M,\gamma}^{\text{SM}}},$$

Exclusive, deriving the bound

- ◆ For a given upper bound we find the following bound:

$$11\kappa_\gamma - 10\kappa_V \sqrt{\bar{\mu}_{J/\psi}/\mu_{ZZ^*}} < \kappa_c < 11\kappa_\gamma + 10\kappa_V \sqrt{\bar{\mu}_{J/\psi}/\mu_{ZZ^*}},$$

$$380\kappa_\gamma - 380\kappa_V \sqrt{\bar{\mu}_\phi/\mu_{ZZ^*}} < \kappa_s < 380\kappa_\gamma + 380\kappa_V \sqrt{\bar{\mu}_\phi/\mu_{ZZ^*}}.$$

GP, Soreq, Stamou & Tobioka (May/15)

- ◆ To project define the following ratios:

$$\bar{\mu}_{M,E} = \bar{\mu}_{M,8} \left(\frac{1}{R_{P,E} R_{\mathcal{L},E} R_{SB,E}} \right)^{1/2},$$

$$R_{SB,E} \equiv \frac{S_E^{\text{SM}}/B_E}{S_8^{\text{SM}}/B_8}, \quad R_{P,E} \equiv \frac{\sigma_{h,E}^{\text{SM}}}{\sigma_{h,8}^{\text{SM}}}, \quad R_{\mathcal{L},E} \equiv \frac{\mathcal{L}_E}{\mathcal{L}_8},$$

- ◆ Projection for $J/\psi \gamma$:

$$\kappa_c < 11 + (75, 42) \left(\frac{1}{R_{SB,14}} \frac{2 \times (300, 3000) \text{ fb}^{-1}}{\mathcal{L}_{14}} \right)^{1/4}, \quad \text{assuming } \mu_{ZZ^*} = \kappa_\gamma = \kappa_V = 1$$

Exclusive, deriving the bound

- ♦ Ratio of signals:

$$\frac{S_\phi}{S_{J/\psi}} = \frac{\sigma_h \text{BR}(h \rightarrow \phi\gamma) \mathcal{L}}{\sigma_h \text{BR}(h \rightarrow J/\psi\gamma) \mathcal{L}} \frac{\text{BR}(\phi \rightarrow K^+K^-)}{\text{BR}(J/\psi \rightarrow \mu^+\mu^-)} \frac{\epsilon_\phi}{\epsilon_{J/\psi}}$$

where $\epsilon_{J/\psi(\phi)}$ is the triggering and reconstruction efficiency

- ♦ Backgrounds: ATLAS=> dominant is jet \rightarrow photon + QCD J/ψ production.

Even more so expected for ϕ :

$$\frac{B_\phi}{B_{J/\psi}} = \frac{\sigma(pp \rightarrow \phi j) P(j \rightarrow \gamma) \mathcal{L}}{\sigma(pp \rightarrow J/\psi j) P(j \rightarrow \gamma) \mathcal{L}} \frac{\text{BR}(\phi \rightarrow K^+K^-)}{\text{BR}(J/\psi \rightarrow \mu^+\mu^-)} \frac{\epsilon_\phi}{\epsilon_{J/\psi}},$$

$$\bar{\mu}_\phi = \bar{\mu}_{J/\psi} \frac{\text{BR}_{J/\psi\gamma}^{\text{SM}}}{\text{BR}_{\phi\gamma}^{\text{SM}}} \sqrt{\frac{\sigma(pp \rightarrow \phi j)}{\sigma(pp \rightarrow J/\psi j)} \frac{\text{BR}(J/\psi \rightarrow \mu^+\mu^-)}{\text{BR}(\phi \rightarrow K^+K^-)} \frac{\epsilon_{J/\psi}}{\epsilon_\phi}} = 0.33 \bar{\mu}_{J/\psi} \sqrt{\frac{\sigma(pp \rightarrow \phi j)}{\sigma(pp \rightarrow J/\psi j)} \frac{\epsilon_{J/\psi}}{\epsilon_\phi}}$$

- ♦ For tight selection (ATLAS) $P(j \rightarrow \gamma) \sim 2 \times 10^{-4}$ & using PYTHIA to simulate QCD BG, and rescaling from $J/\psi\gamma$: $\left. \frac{\sigma(pp \rightarrow \phi j)}{\sigma(pp \rightarrow J/\psi j)} \right|_{\text{Pythia}} \sim 8.5$.

- ♦ Projection for $\phi\gamma$:

$$\kappa_s < 380 + (2900, 1600) \left(\frac{1}{R_{SB,14}} \frac{2 \times (300, 3000) \text{fb}^{-1}}{\mathcal{L}_{14}} \right)^{1/4}$$

Summary

Inclusive (c-tagging): $\kappa_c < 4$;

Exclusive ($J/\psi\gamma$): $\kappa_c < 40$;

Exclusive ($\phi\gamma$): $\kappa_s < 2000$.

GP, Soreq, Stamou & Tobioka (May/15)

- ◆ C-tagging based analysis is just “waiting” for someone to dominate the field.
- ◆ To improve on the exclusive miserable situation, one needs to device new methods, to use the “quiet” nature of the Higgs decay. (new class of jet substructure)
- ◆ What about CMS? Impact of ATLAS new IBL? LHCb?



Conclusions

- ♦ Is the Higgs-mechanism behind the light quark masses?
- ♦ Order one modifications to Higgs light quark (charm) coupling lead to dramatic change in Higgs pheno'.
- ♦ Charm coupling is constrained via charm-tagging, or exclusively.
- ♦ Established higgs-quarks non-universality.
- ♦ Potential for dramatic improve, new phys. window ...
- ♦ What about CMS? Impact of ATLAS new IBL?



LHCb?

Backups

Exclusive modes, projections

Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

- focus on $h \rightarrow \phi\gamma$, use **Pythia 8.1**
 - main decay modes: $\phi \rightarrow K^+K^-$ (49%), K_LK_S (34%), $\pi^+\pi^-\pi^0$ (15%)
 - for $pp \rightarrow h \rightarrow \phi\gamma$ at 14TeV LHC in 70 to 75% cases the kaons/pions and the prompt photon have $|\eta| < 2.4$
 - within the minimal fiducial volume of the ATLAS and CMS experiments
 - adopt the geometrical acceptance factor $Ag = 0.75$
 - do not include other efficiency or trigger factors
 - assume $\kappa_\gamma = 1$, negligible background, 3σ reach

one detector

two detectors

\sqrt{s} [TeV]	$\int \mathcal{L} dt$ [fb $^{-1}$]	# of events (SM)	$\bar{\kappa}_s > (<)$	$\bar{\kappa}_s^{\text{stat.}} > (<)$
14	3000	770	0.56 (-1.2)	0.27 (-0.81)
33	3000	1380	0.54 (-1.2)	0.22 (-0.75)
100	3000	5920	0.54 (-1.2)	0.13 (-0.63)

no theory error

Future experiments

- only a few events expected at e^+e^- colliders
 - ILC, ILC with luminosity upgrade, CLIC
 - probably too small for observation of $h \rightarrow \phi\gamma$
- ≈ 30 events expected at FCC-ee (TLEP)
 - too small to probe a deviation from the SM prediction
- $h \rightarrow \phi\gamma$ measurements unique to future hadron machines

Experimental sensitivity

Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

- focus on $h \rightarrow \phi\gamma$, use $\phi \rightarrow K^+K^- + \pi^+\pi^-\pi^0$ (15%)
- main background is $\pi^+\pi^-\pi^0$
- $\mathcal{S} = |\text{BR}_{h \rightarrow \phi\gamma} - \text{BR}_{h \rightarrow \phi\gamma}^{\text{SM}}| / (\delta \text{BR}_{h \rightarrow \phi\gamma})$, where $(\delta \text{BR}_{h \rightarrow \phi\gamma})^2 = \text{BR}_{h \rightarrow \phi\gamma} / (\sigma_h \mathcal{L} A_g) + (\delta \text{BR}_{h \rightarrow \phi\gamma}^{\text{th}})^2$
- assume $\kappa_\gamma = 1$, negligible background, 3σ reach
- adopt the geometrical acceptance factor $A_g = 0.75$
- do not include other efficiency or trigger factors

\sqrt{s} [TeV]	$\int \mathcal{L} dt$ [fb^{-1}]	# of events (SM)	$\bar{\kappa}_s > (<)$	$\bar{\kappa}_s^{\text{stat.}} > (<)$
14	3000	770	0.56 (-1.2)	0.27 (-0.81)
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100	3000	5920	0.54 (-1.2)	0.13 (-0.63)

two detectors
one detector

Thoughts about experimental strategy

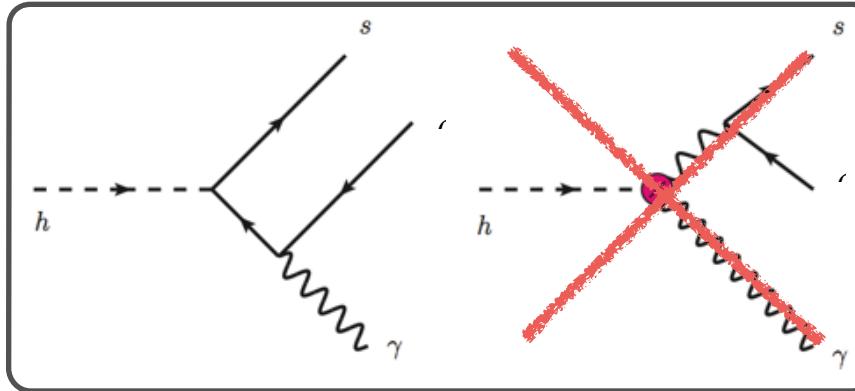
- for $h \rightarrow \phi\gamma$ decay most promising $\phi \rightarrow K^+K^-$
 - near collinearity of the photon and the ϕ -jet in the transverse plane
 - jet sub-structure information
 - two close high- p_T tracks in a narrow cone
 - di-track invariant mass distribution assuming kaons
 - 1.5% (better than 15 MeV) resolution (CMS)
- can probably be used to significantly cut on the background
 - on jet+ γ QCD backgrounds
 - on $h \rightarrow \phi\gamma + n\pi^\circ$, $\eta^{(')}(\rightarrow \text{neutr.})\gamma$
- dedicated trigger probably required to enhance the reach

Thoughts about experimental strategy

- $h \rightarrow \varrho^\circ \gamma$ mode
 - $Br(\varrho^\circ \rightarrow \pi^+ \pi^-) \sim 100\%$
 - relatively clean mode, similar to $\phi \rightarrow K^+ K^-$ decay
- $h \rightarrow \omega \gamma$ mode
 - $Br(\omega \rightarrow \pi^+ \pi^- \pi^\circ) \sim 89\%$
 - harder to trigger on
 - hard-to-identify π° smears the observable quantities
 - a detailed experimental study required

Flavor violating couplings

Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)



- FV modes $h \rightarrow \bar{B}_s^{0*}\gamma, h \rightarrow \bar{B}^{0*}\gamma, h \rightarrow \bar{K}^{0*}\gamma, h \rightarrow D^{0*}\gamma$
 - can probe $\bar{\kappa}_{bs,sb}, \bar{\kappa}_{bd,db}, \bar{\kappa}_{sd,ds}$ and $\bar{\kappa}_{cu,uc}$
- $h \rightarrow \bar{K}^{0*}\gamma$ similar expr. as $h \rightarrow \phi\gamma$
 - but only direct amplitude
- for $\bar{\kappa}_{ds} \sim O(1) \Rightarrow Br(h \rightarrow \bar{K}^{0*}\gamma) \sim O(10^{-8})$
 - not observable at planned future colliders

$$\frac{BR_{h \rightarrow \bar{B}_s^{*0}\gamma}}{BR_{h \rightarrow b\bar{b}}} = \frac{(2.1 \pm 1.0) \cdot 10^{-7}}{0.57 \bar{\kappa}_b^2} \frac{|\bar{\kappa}_{bs}|^2 + |\bar{\kappa}_{sb}|^2}{2},$$

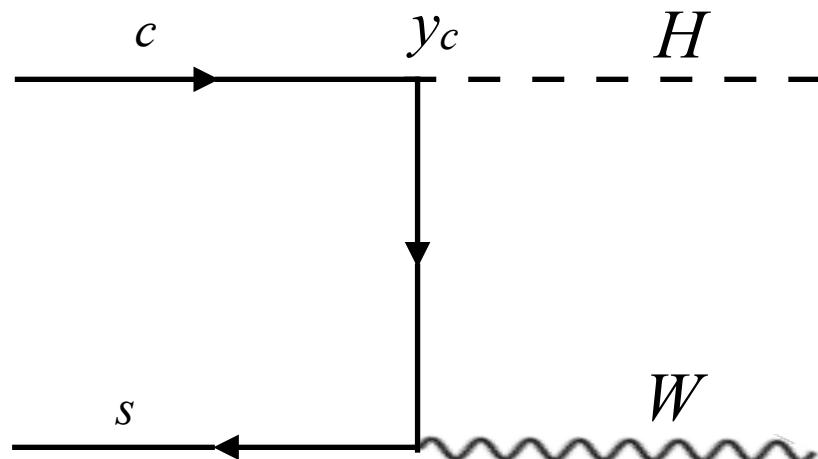
The production via $q\bar{q} \rightarrow h$ in pp with 8TeV are (the SM is 19 pb)

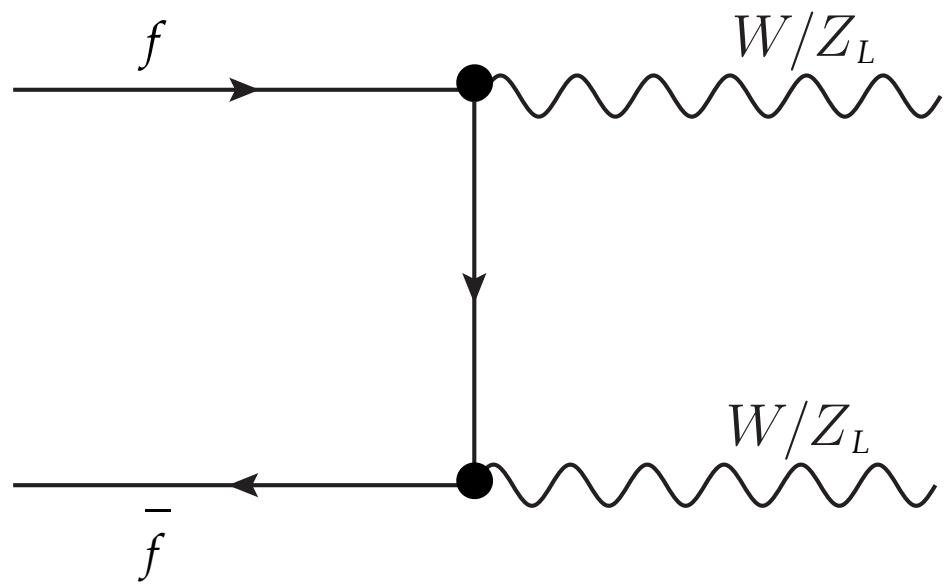
$$\sigma_{u\bar{u} \rightarrow h} = \left(\frac{y_u}{y_b^{\text{SM}}} \right)^2 9.16 \text{ pb},$$

$$\sigma_{d\bar{d} \rightarrow h} = \left(\frac{y_d}{y_b^{\text{SM}}} \right)^2 6.29 \text{ pb},$$

$$\sigma_{s\bar{s} \rightarrow h} = \left(\frac{y_s}{y_b^{\text{SM}}} \right)^2 1.67 \text{ pb},$$

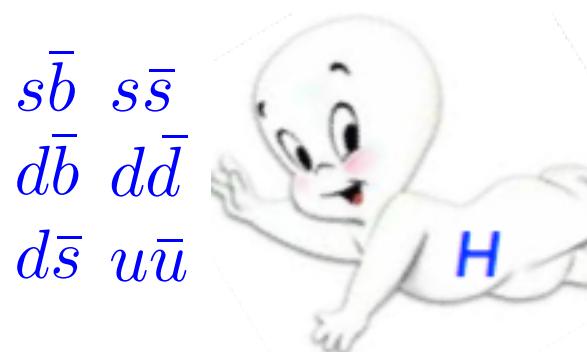
$$\sigma_{c\bar{c} \rightarrow h} = \left(\frac{y_c}{y_b^{\text{SM}}} \right)^2 0.83 \text{ pb}.$$





An Exclusive Window onto Higgs Yukawa Couplings to light quarks

Bodwin, Petriello, Stoynev & Velasco (13)
Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)



Exclusive path towards Higgs-light quark couplings

- ♦ Use the eff. Lagrangian:
$$\mathcal{L}_{\text{eff}} = - \sum_{q=u,d,s} \bar{\kappa}_q \frac{m_b}{v} h \bar{q}_L q_R - \sum_{q \neq q'} \bar{\kappa}_{qq'} \frac{m_b}{v} h \bar{q}_L q'_R + h.c.$$
$$+ \kappa_Z m_Z^2 \frac{h}{v} Z_\mu Z^\mu + 2\kappa_W m_W^2 \frac{h}{v} W_\mu W^\mu + \kappa_\gamma A_\gamma \frac{\alpha}{\pi} \frac{h}{v} F^{\mu\nu} F_{\mu\nu},$$

Notice that: $\bar{\kappa}_q = y_q / y_b^{\text{SM}}$, (sorry different notation)

in the SM:

$$\bar{\kappa}_s = m_s/m_b \simeq 0.020$$

$$\bar{\kappa}_d = m_d/m_b \simeq 1.0 \cdot 10^{-3}$$

$$\bar{\kappa}_u = m_u/m_b \simeq 4.7 \cdot 10^{-4}$$

$$\kappa_\gamma = \kappa_V = 1$$

Exclusive path towards Higgs-light quark couplings

Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

♦ Use the eff. Lagrangian:

$$\begin{aligned} \mathcal{L}_{\text{eff}} = & - \sum_{q=u,d,s} \bar{\kappa}_q \frac{m_b}{v} h \bar{q}_L q_R - \sum_{q \neq q'} \bar{\kappa}_{qq'} \frac{m_b}{v} h \bar{q}_L q'_R + h.c. \\ & + \kappa_Z m_Z^2 \frac{h}{v} Z_\mu Z^\mu + 2\kappa_W m_W^2 \frac{h}{v} W_\mu W^\mu + \kappa_\gamma A_\gamma \frac{\alpha}{\pi} \frac{h}{v} F^{\mu\nu} F_{\mu\nu}, \end{aligned}$$

Notice that: $\bar{\kappa}_q = y_q / y_b^{\text{SM}}$,

where generically: $|\bar{\kappa}_u| < 0.98, |\bar{\kappa}_d| < 0.93, |\bar{\kappa}_s| < 0.70$

varying only one at the time (95%CL)

$|\bar{\kappa}_u| < 1.3, |\bar{\kappa}_d| < 1.4, |\bar{\kappa}_s| < 1.4$

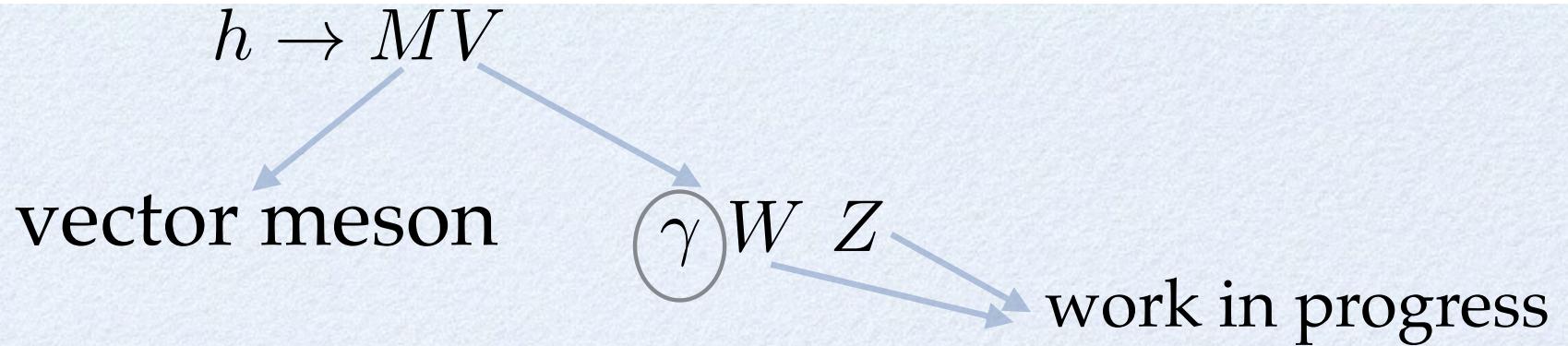
varying all couplings (95%CL)

$|\bar{\kappa}_{qq'}| < 0.6$ (1) for $q, q' \in u, d, s, c, b$ and $q \neq q'$

same for the flavor violating case

(FCNC non-robust bound: $|\bar{\kappa}_{bs}| < 8 \cdot 10^{-2}$) Harnik, Kopp & Zupan; Blankenburg, Ellis, Isidori, (12)

The main idea



Bodwin, Petriello,
Stoynev, Velasco
1306.5770

$$h \rightarrow J/\psi \gamma \longrightarrow y_c$$

$$\begin{aligned} \phi\gamma &\longrightarrow y_s \\ h \rightarrow \rho\gamma &\longrightarrow y_d, y_u \\ \omega\gamma &\longrightarrow y_d, y_u \end{aligned}$$

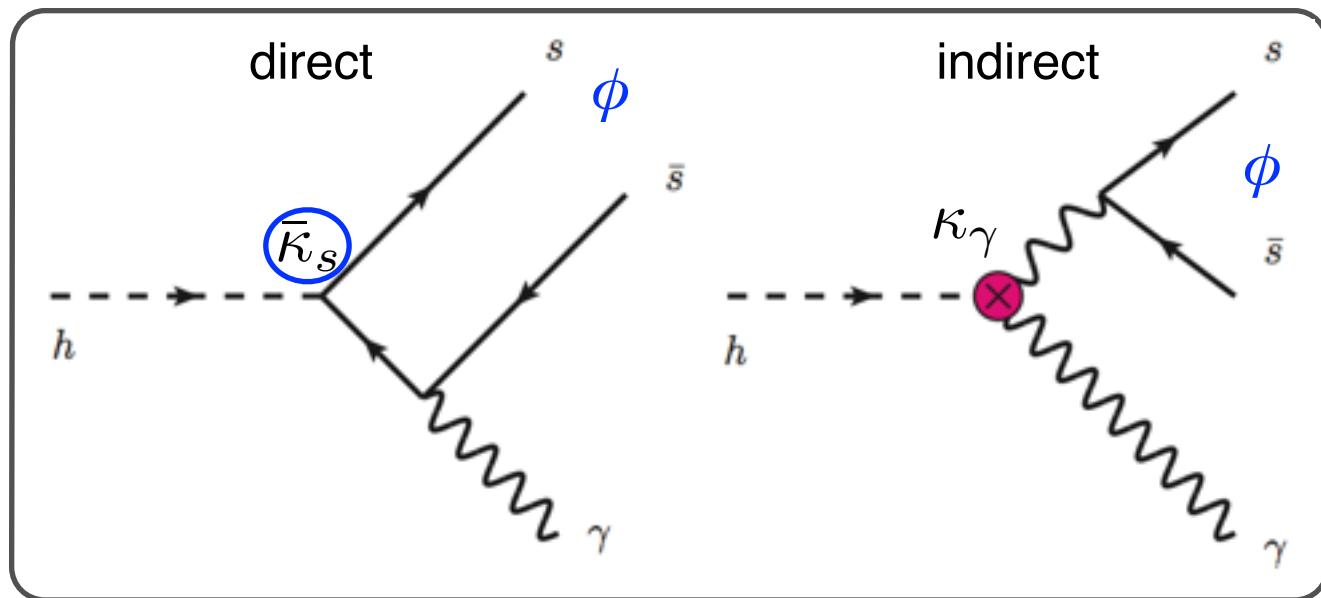
Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

Adding off-diagonal: $h \rightarrow \bar{B}^{0*}\gamma, h \rightarrow \bar{B}^{0*}\gamma, h \rightarrow K^{0*}\gamma, h \rightarrow D^{0*}\gamma$

Ex.: $h \rightarrow \phi\gamma$

$$\Gamma_{h \rightarrow \phi\gamma} = \frac{1}{8\pi} \frac{1}{m_h} |M_{ss}^\phi|^2,$$

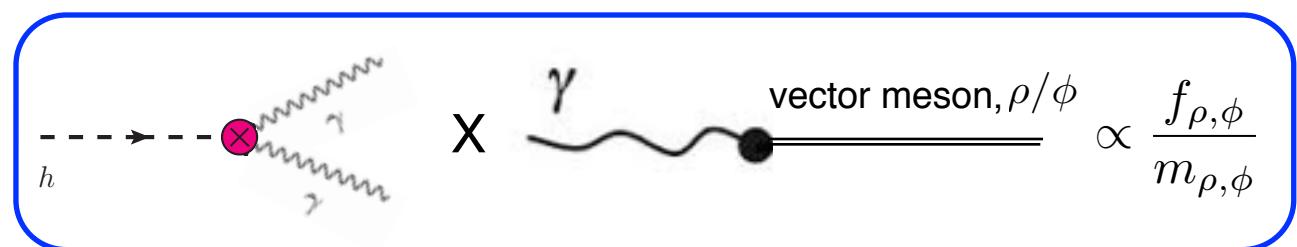
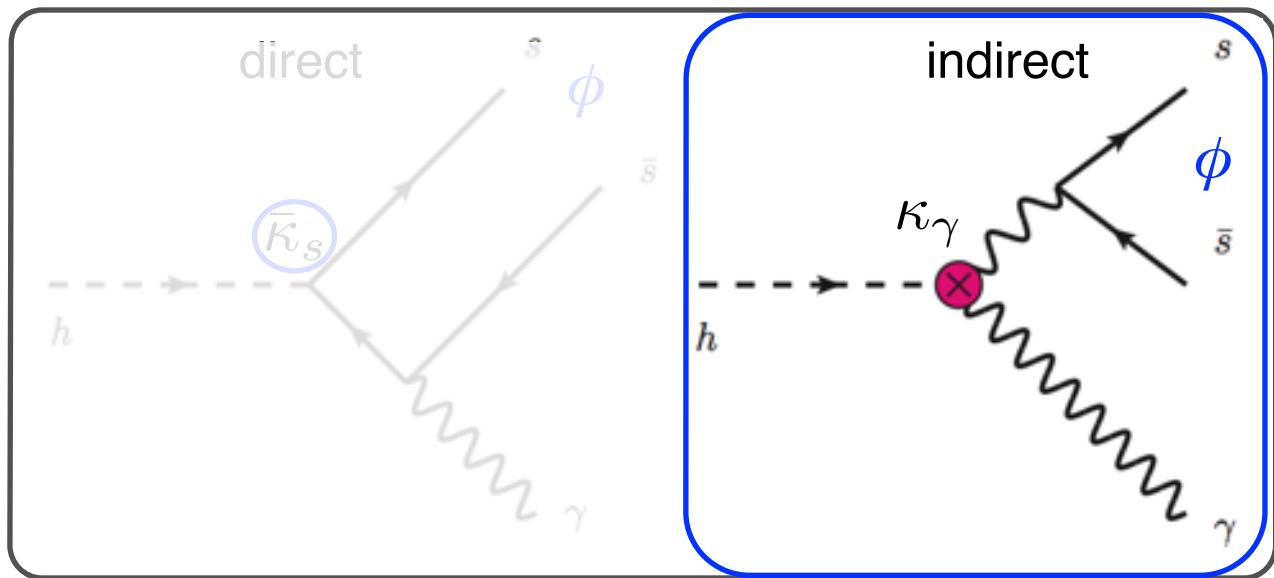
- Two paths to get $h \rightarrow \phi\gamma$:



- Let us understand them one by one.

Ex.: $h \rightarrow \phi\gamma$, indirect contribution

- Two paths to get $h \rightarrow \phi\gamma$:



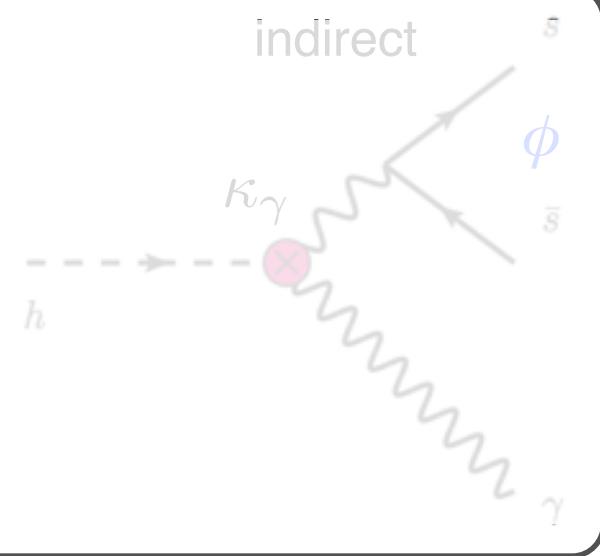
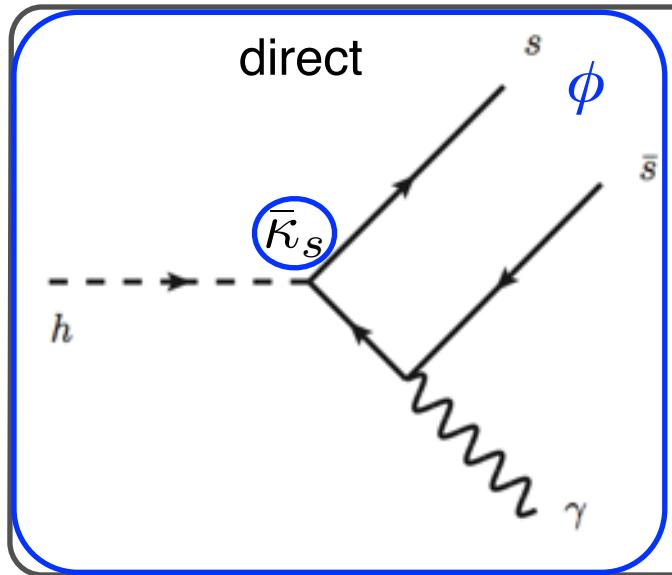
$\propto \frac{f_{\rho,\phi}}{m_{\rho,\phi}}$

(from experiment, $\phi \rightarrow e^+e^-$)
 $f_\phi = 0.235(5) \text{ GeV}$

$$(M_{ss}^\phi)_{\text{indir}} \approx \frac{f_{\rho,\phi}}{m_{\rho,\phi}} \kappa_\gamma A_\gamma \frac{4\alpha m_h^2}{\pi v}$$

Ex.: $h \rightarrow \phi\gamma$, direct contribution

- Two paths to get $h \rightarrow \phi\gamma$:



$$\propto \frac{\bar{\kappa}_s m_b}{v} \frac{f_{\rho,\phi}^\perp}{m_h}$$

("local" structure : $\bar{s}\sigma_{\mu\nu}s \times F^{\mu\nu}$)

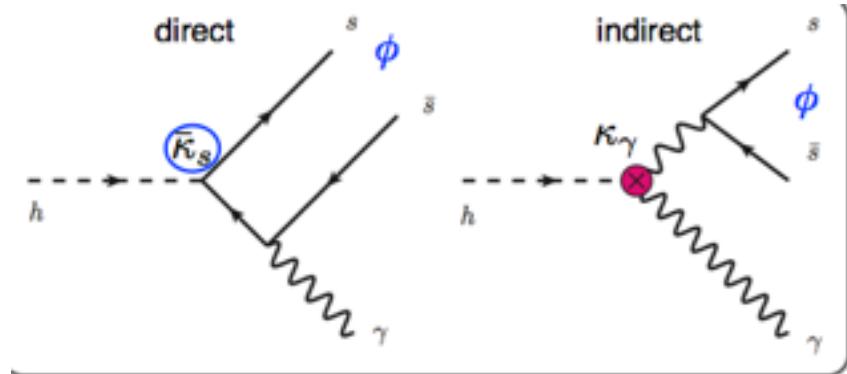
from experiment, $\phi \rightarrow e^+e^-$

$$(f_\perp^\phi = 0.191(28))$$

$$(M_{ss}^\phi)_{\text{dir}} \approx \frac{\bar{\kappa}_s m_b}{v} f_\phi^\perp$$

Final result for the $\text{BR}(h \rightarrow \phi\gamma)$

$$\Gamma_{h \rightarrow \phi\gamma} = \frac{1}{8\pi} \frac{1}{m_h} |M_{ss}^\phi|^2,$$



- ◆ The resulting sensitivity:

$$\frac{\text{BR}_{h \rightarrow \phi\gamma}}{\text{BR}_{h \rightarrow b\bar{b}}} = \frac{\kappa_\gamma [(3.0 \pm 0.3)\kappa_\gamma - 0.78\bar{\kappa}_s] \cdot 10^{-6}}{0.57\bar{\kappa}_b^2},$$

$$\frac{\text{BR}_{h \rightarrow \rho\gamma}}{\text{BR}_{h \rightarrow b\bar{b}}} = \frac{\kappa_\gamma [(1.9 \pm 0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d] \cdot 10^{-5}}{0.57\bar{\kappa}_b^2},$$

$$\frac{\text{BR}_{h \rightarrow \omega\gamma}}{\text{BR}_{h \rightarrow b\bar{b}}} = \frac{\kappa_\gamma [(1.6 \pm 0.17)\kappa_\gamma - 0.59\bar{\kappa}_u - 0.29\bar{\kappa}_d] \cdot 10^{-6}}{0.57\bar{\kappa}_b^2},$$

Similar holds
for 1st generation:

Charming the Higgs, current status & few projections

Delaunay, Golling, GP & Soreq (13)

- ♦ Ball park bounds are from Higgs “invisible” bound (assumes $c_v=1$):

if all other “visible” couplings set to SM values:

$$Br_{inv} \sim < 22\% @95\%CL$$

adding a new physics source of ggh: $Br_{inv} \sim < 50\% @95\%CL$

$BR(H \rightarrow b\bar{b})$ is significantly suppressed:

$$BR_{h \rightarrow b\bar{b}} = \frac{BR_{h \rightarrow b\bar{b}}^{\text{SM}}}{1 + (|c_c|^2 - 1)BR_{h \rightarrow c\bar{c}}^{\text{SM}}} \approx 40\% (20\%)$$

with $c_{gg} > 0$

$$\begin{aligned} \hat{c}_{gg} &= c_{gg} + \left[1.3 \times 10^{-2} c_t - (4.0 - 4.3i) \times 10^{-4} c_b \right. \\ &\quad \left. - (4.4 - 3.0i) \times 10^{-5} c_c \right], \end{aligned}$$

$$\sigma_{c\bar{c} \rightarrow h} \simeq 3.0 \times 10^{-3} |c_c|^2 \sigma_{gg \rightarrow h}^{\text{SM}},$$

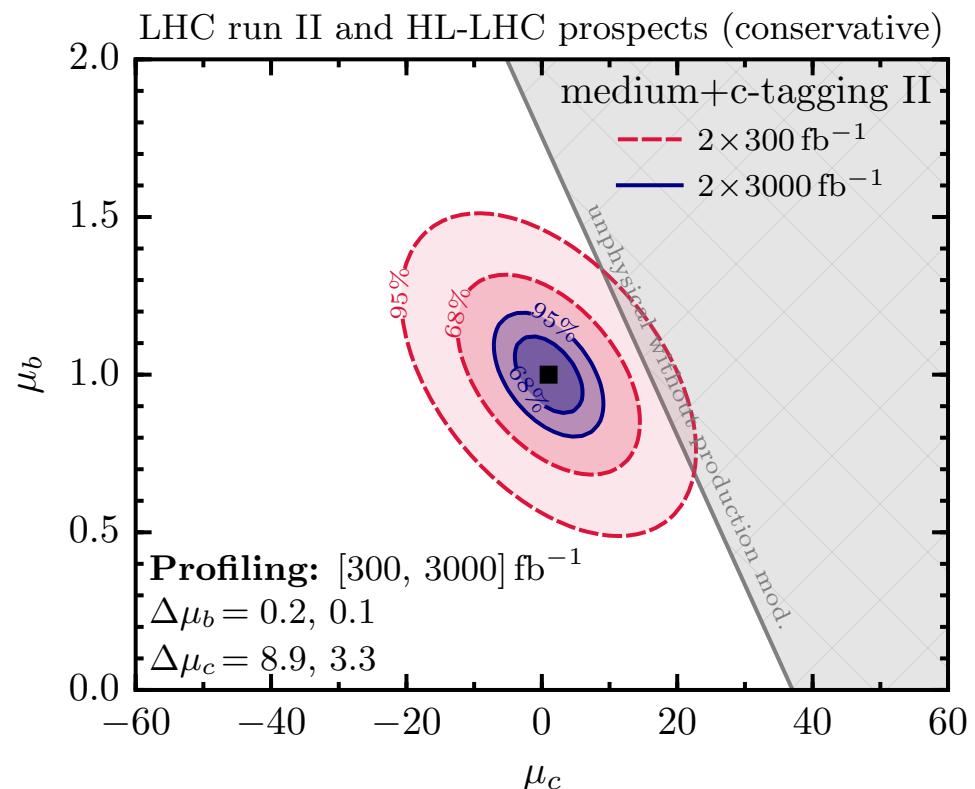
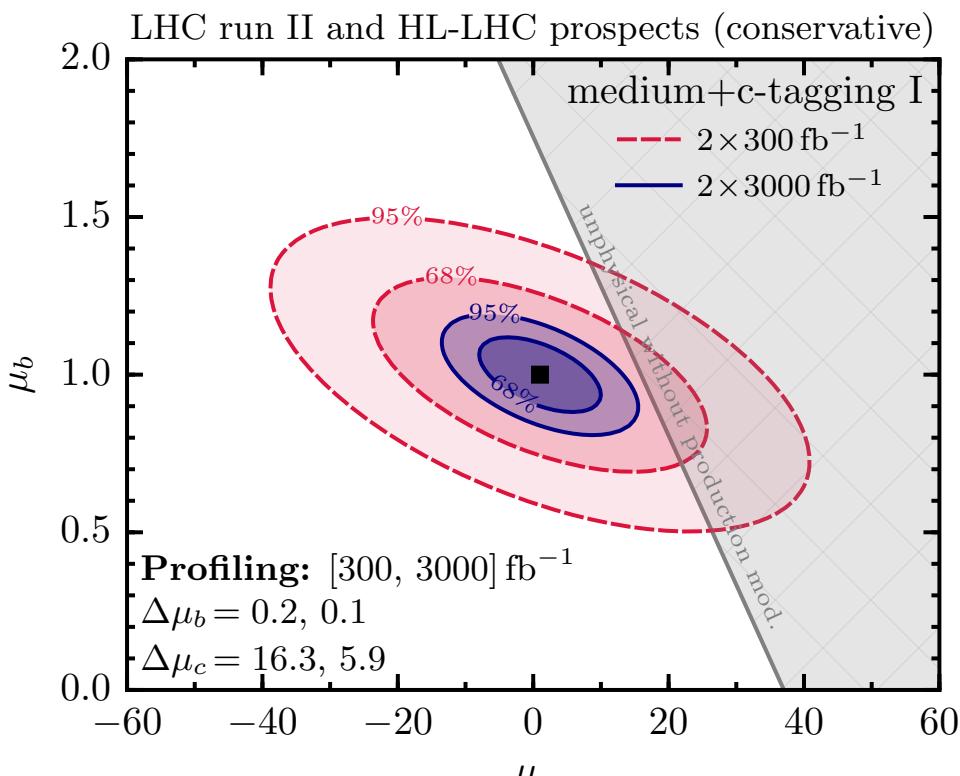
assume instead a speculative $\varepsilon_c = 40\%$ c-tagging efficiency:

$$\rightarrow \mu_{bb+cc} \approx 0.9 (0.6) @8\text{TeV}$$

projections

LHC14, significant improvement inclusive c-tagging

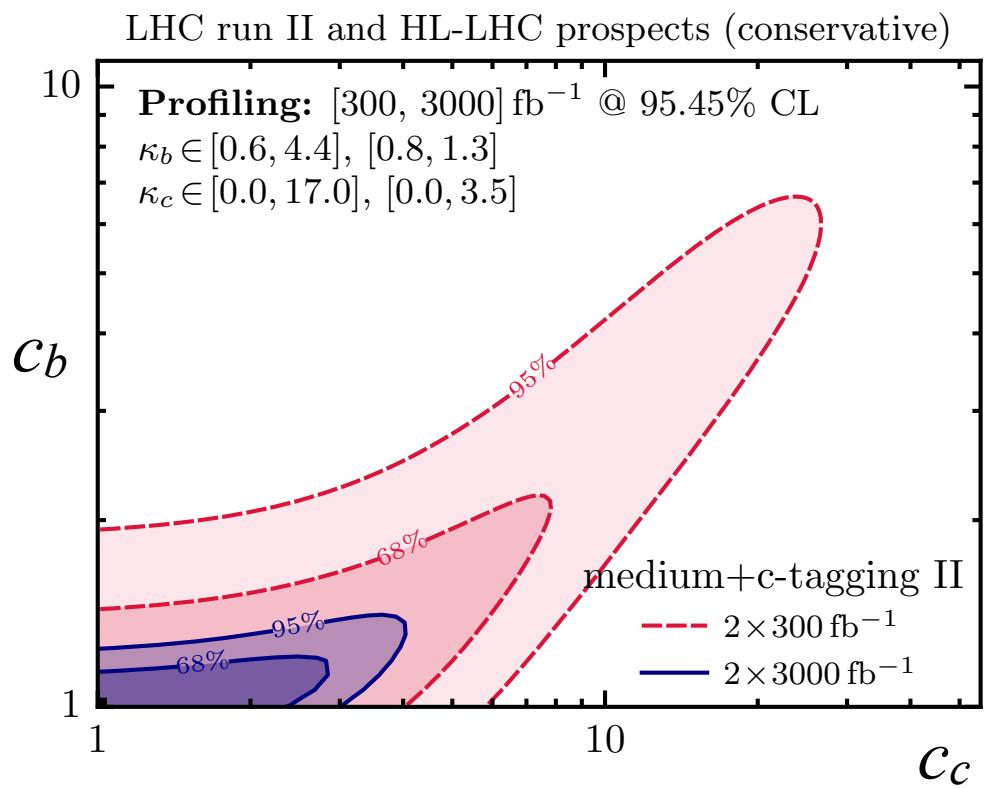
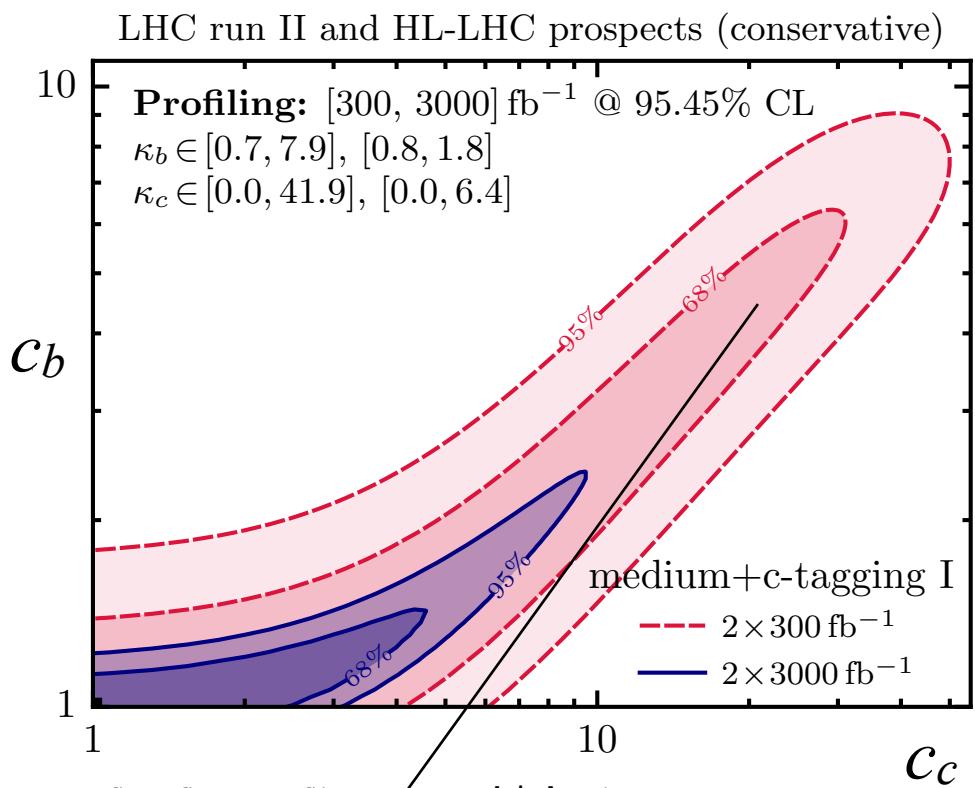
	ϵ_b	ϵ_c	ϵ_l
Medium	70%	20%	1.25%
C-tagging I	13%	19%	0.5%
C-tagging II	20%	30%	0.5%



GP, Soreq, Stamou & Tobioka to appear

LHC14, significant improvement inclusive c-tagging

	ϵ_b	ϵ_c	ϵ_l
Medium	70%	20%	1.25%
C-tagging I	13%	19%	0.5%
C-tagging II	20%	30%	0.5%



Flat direction when: $\mu_c \text{BR}_{cc}^{\text{SM}} + \mu_b \text{BR}_{bb}^{\text{SM}} = 1, \Rightarrow c_b^2 = c_c^2 \frac{\mu_c}{\mu_b}$

Prelim: naive exclusive projections, $h \rightarrow J/\psi\gamma$ (c_c)

- ◆ Defines some ratios to rescale sensitivity from ATLAS result: (x subscript for future)

$$R_{SB} = \frac{\sigma_S^8}{\sigma_B^8} \frac{\sigma_B^X}{\sigma_S^X}, \quad R_P = \sigma_{pp \rightarrow h}^X / \sigma_{pp \rightarrow h}^8, \quad R_{\mathcal{L}} = \mathcal{L}_X / \mathcal{L}_8.$$



$$\bar{\mu}_S^X = \bar{\mu}_S^8 \sqrt{\frac{R_{SB}}{R_P R_{\mathcal{L}}}},$$

- ◆ Assuming SM production: $\overline{\text{BR}}_{J/\psi\gamma}^X = \overline{\text{BR}}_{J/\psi\gamma}^8 \sqrt{\frac{R_{SB}}{R_P R_{\mathcal{L}}}},$

$$\overline{\text{BR}}_{J/\psi\gamma}^{14} = 2.4 \times 10^{-4}, 5.4 \times 10^{-5} \sqrt{R_{SB} \frac{300,6000 \text{ fb}^{-1}}{\mathcal{L}_{14}}},$$

$$11 - (95, 45) \left(R_{SB} \frac{300,6000 \text{ fb}^{-1}}{\mathcal{L}_{14}} \right)^{1/4} < \kappa_c < 11 + (95, 45) \left(R_{SB} \frac{300,6000 \text{ fb}^{-1}}{\mathcal{L}_{14}} \right)^{1/4}$$